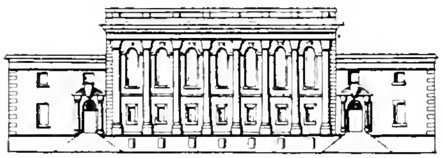

THE DEVELOPMENT OF SUPPLEMENTARY EXPERIMENTS FOR INSTRUMENTAL ANALYSIS

by

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INTRODUCTION

There is a general trend in chemistry today towards the use of precision instruments for faster, more accurate analytical work. Today's chemist must therefore be familiar with the general principles of electronics so that he may effectively use the instruments he has. He must also have a good idea of what kinds of components he would need, how precise and expensive they are, and how they could best be used in developing new instrumental methods or in improving on present methods. A chemist must also have some idea of how to repair the instruments he uses, or at least how to locate trouble, since repair bills can be expensive and instruments which are not in operating order present a tremendous financial loss. The proper care of the instruments must also be considered in order to prevent unnecessary damage.

Courses in electronics are available for chemistry students in college, but these generally have serious drawbacks for the smaller liberal arts colleges. One of the finest courses is one designed by H. V. Malmstadt and C. G. Enke. The course uses educational instruments supplied by Heath Co. (Benton Harbor, Michigan), the total cost of which is about $1,000. The book which accompanies the course, Electronics for Scientists, is a very comprehensive reference for electronics and instrument design. The course, however, is designed to take an entire semester (15 weeks) which includes four to five hours of laboratory work per week and an equal amount of outside work. Each student must also have the complete set of equipment available for his individual use during the laboratory period.[1] This would mean, at Sweet Briar, another whole course for chemistry and other science majors, with a professor required to help with the laboratory and with much expensive equipment needed. This makes the course extremely impractical for a small college such as Sweet Briar.

It was also felt that this course did not develop as good a basic understanding of the principles of electricity as is desirable. It was therefore my intention to design a laboratory for the existing course in instrumental analysis that would incorporate the principles of the instruments involved and their uses in chemical analysis.

The manner in which it was felt that this could best be accomplished

was to design and construct readily understandable ciruits which would not only show the principles of electronics but which also could be used in making chemical measurements. These principles may then easily be extended to more complicated instruments where refinements in circuitry and design allow more precision but where the basic components are still the same. The Beckman Model G pH meter is really no more than an amplifier and a potentiometer with the scale marked in pH units, so if the principles of a simple amplifier and of a potentiometer are already understood, the operation of the pH meter should also be understood.

The order in which the experiments are performed allows the student to build on previously developed principles and also to use these principles in actual chemical analyses as they are presented so that the relevance of the laboratory is emphasized.

In order to clarify the circuits, a breadboard was used in most of the work, and the components were arranged on it so that the circuits would appear on the board much as they appear in the circuit diagrams. For simplicity, peg board was used with $\frac{6}{32}$ machine screws and nuts for terminals. Wherever it was necessary to inter-change components or wires, these were equipped with a spring clip of the type developed by Malmstadt and Enke. These could then easily be clipped onto the terminals.[2]

Not all circuits have been completed, but the general ideas and the directions that further circuits might take have been considered. The whole laboratory will probably require ten weeks with two three-hour laboratory periods a week. It will include dc and ac circuits, potentiometry and potentiometric titrations, electrogravimetry, polarography, conductivity and conductometric titrations, power supplies, amplifiers, and an opportunity for the student to do special projects such as constant current coulometry or more detailed work with any of the above methods. Most of the chemical theory will be presented during the lectures, but a good deal of the theory of instrumentation will actually be demonstrated in the laboratory.

In all the work, a background of a basic course in physics has been assumed, but an explanation of principles or reference to appropriate sources has been included with the laboratory directions. A list of related problems is also included with some of the work, and each laboratory should include questions.

Because of the nature of the research, this report has been written as a laboratory manuel, with results, answers and conclusions following the directions for each experiment. The experimental results were obtained to show that the instruments designed may indeed be used in the manner described, but no attempt was made to obtain very precise results.

# DIRECT CURRENT DETECTORS AND THE MULTIMETER

One of the most basic problems of electrochemical methods is that of measuring currents and voltages. A lightbulb, when placed in a circuit through which current is flowing or when placed across a potential difference, will light up, but although the intensity of the light may change with changes in current or potential, this does not give a sufficiently accurate quantitative measurement. By using the relation between a moving charge and a magnetic field however, it is possible to build a very sensitive linear current detector which, with suitable modifications of the external circuit, may be used to measure voltages and resistances as well.

In the discussion which follows, it is assumed that the student is familiar with Ohm's law and series and parallel resistance circuits. A list of problems which may serve as a helpful review may be found at the end of the paper.

A moving charge sets up a magnetic field around it. Since a current involves the motion of electrons, a wire carrying a current has a magnetic field associated with it, as illustrated in figure 1.

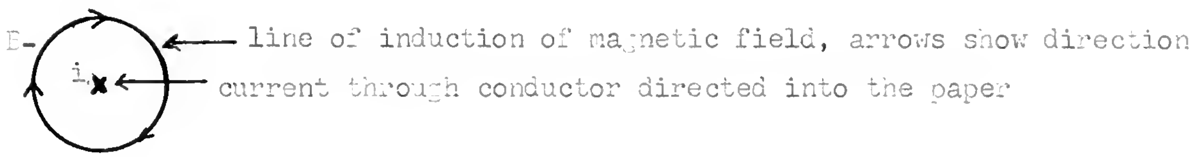


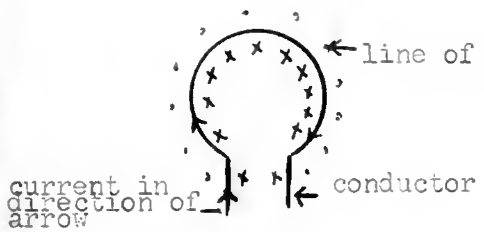

Figure 1

The direction of B, the magnetic field, may always be determined by holding the wire in the right hand with the thumb along the wire, pointing in the direction of the conventional current. The magnetic field is then in the direction of the fingers.

The magnetic field, B, lies in the plane normal to the direction of the current and its direction is always at right angles to the direction of the current, and is therefore in a circle around the conductor. By convention, the arrow of B points to the north. If a compass were then placed on a wire carrying a current, the needle would be deflected such that the north end of

the needle would line up with the south of the magnetic field established by the current. If the compass were then placed under the wire, the needle would still be deflected, but this time in the opposite direction.

A wire which is bent in a circle and which carries a current also has a magnetic field associated with it, as is shown in Figure 2:

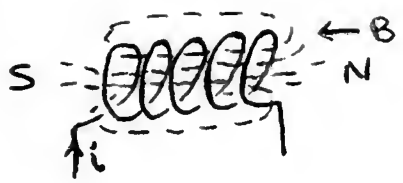



·represents B out of paper

x represents B into paper

Figure 2

The net effect of this is that the circle of wire is a magnetic dipole, a little magnet. If the wire is then coiled, a current passing through this coil produces an even larger magnetic dipole as is illustrated in Figure 3:

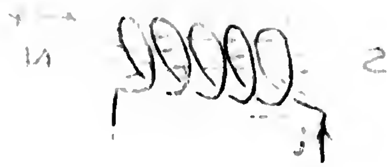



The direction of the field due to current through a coil may be determined by holding the coil in the right hand so that the fingers curl in the direction of the current flow. The thumb then points to the north.

Figure 3

If this coil were then suspended at right angles to a magnetic field, whenever there was a current in the coil, it would experience a torque and tend to rotate so that the north end of the coil would be aligned with the south of the field. This is the principle on which an ammeter is based.

A very fine coil is suspended between the poles of a horseshoe magnet by a spring which keeps it normally perpendicular to the field of the magnet (see Figure 4), and a pointer is attached. When current flows in the coil, it becomes a small magnet with B in the direction indicated, and it tends to turn so that it is parallel to the field of the horseshoe magnet. However,



the spring exerts a force in the opposite direction and therefore opposes the motion of the coil. The amount that the coil actually moves is proportional to the current because the magnitude of $F$ is proportional to the

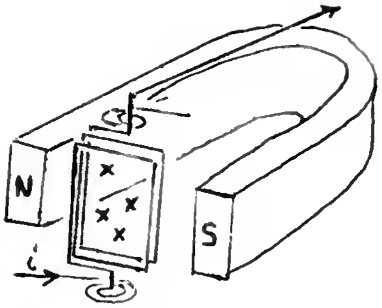



Figure 4[3]

magnitude of the current. The pointer indicates the movement of the coil and, if a suitable scale is attached, this becomes an accurate method for measuring current. It is known as a D'Arsonval meter and may be used in either an ammeter or in a galvanometer. The latter may deflect in either direction, depending on the direction in which the current flows, while the former may be used only with current in one direction.

An ammeter, then, is used to measure currents. In order to do this, it must be connected in the circuit in series so that the current passes through it. From Ohm's law, $V=iR$, however, it is seen that the current will change if the total resistance of the circuit changes. Putting a current measuring device of significant resistance into the circuit will therefore change the current being measured. Ideally, the resistance of an ammeter would be zero, but since every coil has some resistance, this is not possible. If, however, the resistance of the ammeter is small with respect to the other components of the circuit, the change in current will be negligible. Therefore it is desirable to have ammeters with low resistance.

An ammeter may be used to measure several current ranges by use of a suitable shunt resistor. This is a resistor connected in parallel with the meter which then carries part of the current flowing in the circuit.

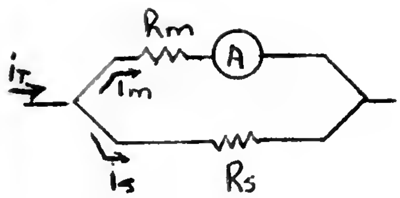



Figure 5

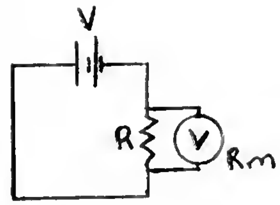
Figure 5 illustrates the shunting circuit. $R_m$ is the internal resistance of the ammeter, $R_s$ the shunt resistance, $i_s$ and $i_m$ are the currents through $R_s$ and $R_m$ respectively, and $i_t$ is the total current in the circuit.

If $R_s$ is adjusted such that only 1/10 of the total current flows through the meter, then the total current would be ten times as great as the meter reading. Thus the smaller the value of the shunt resistor, the larger the range of the ammeter.

An ammeter may also be used to measure voltages by application of Ohm's law. If an ammeter of known resistance is placed across an unknown voltage, the current which flows through the ammeter will be proportional to the voltage and the proportionality constant will be the resistance of the ammeter. That is, $V_{unknown} = i_{through\ meter} x R_{meter}$.

If the resistance of the ammeter is adjusted properly, the scale of the ammeter may be a suitable scale fo reading voltages directly. For example, if an ammeter has a range from 0 to 10 ma and its resistance is 1000 $\Omega$, then full scale deflection when it is placed across a voltage would indicate a voltage of 1000 x 10 x $10^{-3}$a or 10 volts. Most ammeters, however, do not have this large a resistance. By placing appropriate resistors in series with the ammeter, though, the total resistance may be increased to a convenient value. An ammeter may then serve as a voltmeter of many ranges simply by changing its resistance.

Because a voltmeter is used to measure the voltage drop across two points in a circuit, it is always placed in parallel. If one uses it to measure the voltage drop across a resistor however, one changes the total resistance of the circuit and hence the current flowing in the circuit. Since the voltage drop across a resistor is proportional to the current through it, the voltage being measured will be changed by insertion of the measuring device. However, if relatively little current is drawn by the voltmeter, the change in voltage will be small. Therefore a voltmeter should have a large resistance with respect to the resistances in the circuit. Figure 6 illustrates a circuit





voltmeter having some resistance, $R_m$, associated with it

Figure 6

for measuring voltage drop.

One single ammeter may then be used to make a multimeter, a combination voltmeter and ammeter having several scales for each function, by the choice of suitable resistors and the correct use of these in the external circuit.

Suggested references for review of dc circuits:


1. Brophy, Basic Electronics for Scientists, McGraw-Hill Book Compnay, New York, 1966, chpt. 1.

2. Malmstadt and Enke, Electronics for Scientists, W.A. Benjamin, Inc., New York, 1962, chpt. 1 and supplement 2.

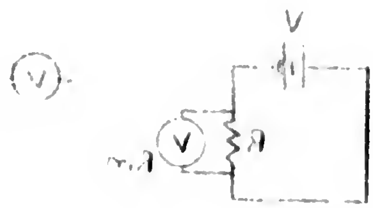
3. Reilley and Sawyer, Experiments for Instrumental Methods, McGraw-Hill Book Company, Inc., New York, 1961, pp. 294-298.

4. Sears, Electricity and Magnetism, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 194?, chaps. 5 and 10.

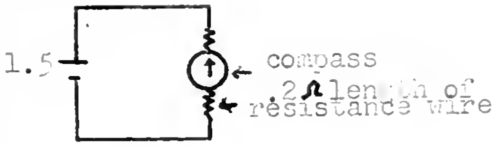

Procedure

Place a small compass on top of a resistance wire so that the compass needle is parallel to the wire. (How must you place the wire with respect to the earth's magnetic field?) Connect a 1.5 volt dry cell to the wire and observe the deflection of the compass needle. Reverse the direction of the current (How?) and again note the needle deflection. Place the compass under the wire with the needle still parallel and repeat the above procedure. Explain your observations in terms of the magnetic field around the current-carrying wire and verify the right hand rule for field direction.

Next take a coil of wire and align the compass needle so that it parallels the coil. Again connect the 1.5 volt dry cell and observe the needle deflection. Reverse the field. (What would be a better way to align the needle with respect to the coil?) Again verify the right hand rule.



Do not keep the coil or wire connected to the dry cell for any length of time since they both have low resistance and will draw large currents and drain the battery.



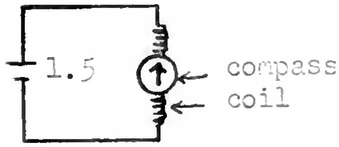




Figure 7

Look at the broken ammeter which has been taken apart. Observe the coil and springs. Also observe the magnet in the Leeds and Northrup galvanometer.

In the following experiments, a Heath vacuum tube voltmeter (VTVM) is used as an accurate voltage measuring device to calibrate other meters. The VTVM may be used as a very accurate, high resistance Voltmeter. For further information, see Reference 2, pp. 23-25.

The resistance of an ammeter may be determined by the following circuit (Figure 8)[4]:

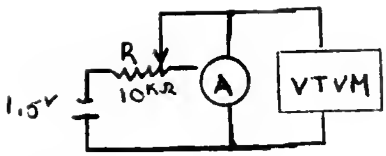


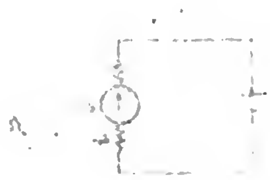

Figure 8

Using an ammeter with a 0-15 ma range, adjust R so that the meter is deflected to full scale, measure the voltage across the meter and calculate $R_m$, the meter resistance, from Ohm's law.

Calculate the resistances needed to convert the ammeter to a 0-150ma meter range; to a 0-1.5a . meter range. (How would you connect them?)

Calculate the resistances needed to convert the ammeter to a voltmeter having a 0-15v range; a 0-75v range; a 0-150v range.

Show the circuits you would use for each of these ranges and uses, including one for a 0-15ma ammeter.



When your circuit diagrams have been approved, you will be given a peg board with the appropriate resistors attached. Some of these may not be the exact size that was calculated. Do your calculated values fall within the limits of tolerance of the resistors? (Assume 1%)

Calibration of the meter

Connect the meter for the 0-15ma ammeter scale. Use a 1.5v dry cell and a decade box in the following circuit:

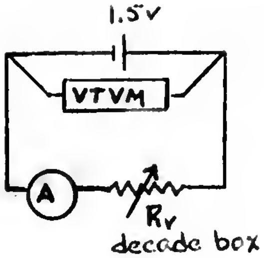



Figure 9

Be sure the decade box is set to at least 100 Ω before connecting the ammeter. (Why?)

The resistance of the meter has already been determined. The resistance of the decade box is varied and the current at each setting noted. The total voltage across the circuit is obtained from the vacuum tube voltmeter, and the actual current value is calculated from $V=i(R_m + R_v)$. Plot these values against the values for the current given by the meter.

Then connect the meter for the 0-15v scale. Using a variable voltage source, plot the voltages given by the multimeter versus those of the VTVM using the following circuit:

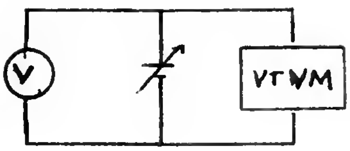
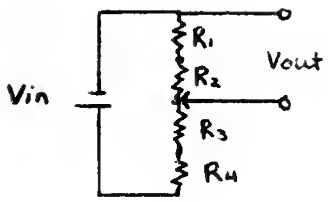



Figure 10

Note: (V) represents the combination of (A) plus the resistance.

Why should the VTVM and the mustimeter both be connected across the power supply when taking measurements? A variable voltage source usually uses a voltage

divider. This is just a series of resistors with a voltage applied across them, and the output taken across the resistors. The ratio of the resistance across which the voltage is taken to the total resistance is proportional to the ratio o the voltage taken to the total voltage.



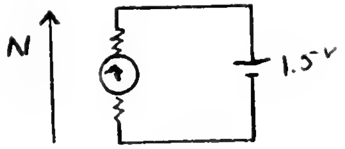

$$\frac{V_{out}}{V_{in}} = \frac{R_1 + R_2}{R_1 + R_2 + R_3 + R_4}$$

Voltage Divider
Figure 11

The other ammeter and voltmeter scales could be calibrated in the same manner, using appropriate voltage sources. Because the use of relatively high voltages is involved, however, the calibration curves will be given to you. These curves should be used everytime the multimeter is used.

## Calculations, data and conclusions

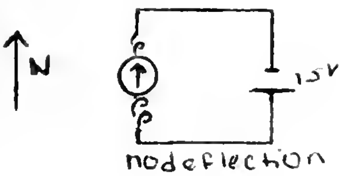
The north end of the compass needle aligns itself with the south of the earth's magnetic field. If the wire is placed so that it is parallel to the earth's magnetic field, the needle will parallel the wire.

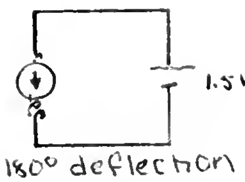



When the compass was on top of the wire, the needle was deflected in a counter-clockwise direction; when it was under the wire, the needle was deflected in a clockwise direction.

When the direction of the current was reversed by reversing the battery, the deflection directions were reversed.

When the coil was connected in one direction, there was no needle deflection. When the voltage was reversed, the needle was deflected 180°.



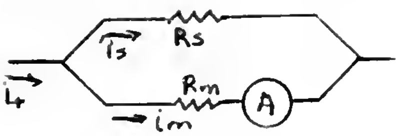

The right hand rule predicted the direction of deflection successfully.

It would be better to place the coil perpendicular to the earth's field so that an equal and opposite deflection would be observed when the voltage was applied and reversed.

The voltage across the ammeter at full scale deflection (15ma) was 0.3v. The resistance was then calculated:

$$V = iR_m \qquad R_m = \frac{V}{i} \qquad R_m = \frac{0.3}{0.015} = 20\,\Omega$$

For the meter to have a 0-150ma range, only 1/10 of the total current can flow through the meter.




$i_t = i_s + i_m$ The voltage drop across $R_s$ and $R_m$ must be the same. Therefore, $i_sR_s = i_mR_m$.

$$i_m = \frac{1}{10}i_t \qquad i_s = \frac{9}{10}i_t \qquad \frac{9}{10}i_tR_s = \frac{1}{10}i_tR_m \qquad R_s = \frac{R_m}{9} = \frac{20}{9} = 2.2\,\Omega$$

For the meter to have a 0-1.5a range, only 1/100 of the total current may flow through the meter.

$$i_t = \frac{1}{100} i_t + i_s \qquad \therefore \quad i_s = \frac{99}{100} i_t \; ; \qquad \frac{99}{100} i_t R_s = \frac{1}{100} i_t R_m$$

$$R_s = \frac{R_m}{99} = \frac{20}{99} = 0.20\ \Omega$$

For a voltmeter of 0-15v range, 15ma must flow through the meter circuit when it is put across 15v. The total resistance of the meter circuit must therefore be $\frac{15v}{15x10^{-3}a} = 1000\Omega$. Since $R_m = 20\Omega$, a 980Ω resistor must be used in series with the meter.

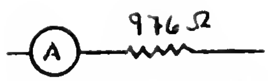
For a voltmeter of a 0-75v range, 15ma must flow when 75v are applied. The total resistance must then be $\frac{75}{15x10^{-3}} = 5000\Omega$. A 4980Ω resistor should therefore be used in series with the meter.

For a range of 0-150v, 15ma must flow when 150v are applied. Therefore the total resistance must be $\frac{150}{15x10^{-3}} = 10k\Omega$, and the resistance needed in series with the meter is 9980Ω.

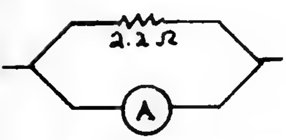
The resistors actually available were 2.2Ω, 0.2Ω (resistance wire), 976Ω, 4990Ω, and 10kΩ. If 1% tolerance is assumed for the larger resistors, this means that the 976Ω resistor has a resistance between 966Ω and 986Ω so this is adequate for the 980Ω resistor. The 4990Ω resistor may vary between 4940Ω and 5040Ω and the 10kΩ resistor may vary between 9900Ω and 11000Ω so these may replace the 4980Ω and 9980Ω resistors respectively.

The following circuits would then be used:

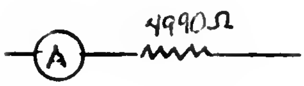
0-15ma ammeter



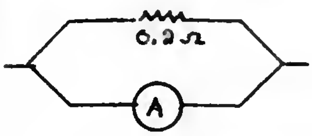

0-15v voltmeter



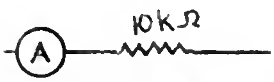

0-150ma ammeter




0-75v voltmeter

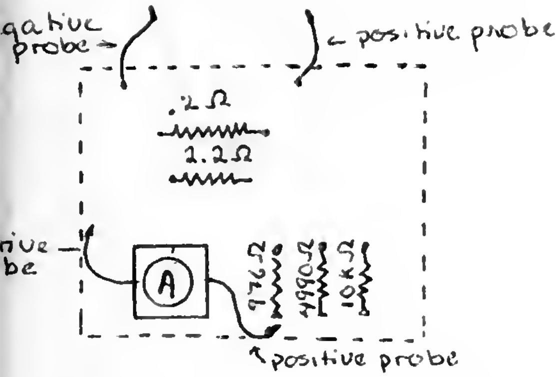



0-1.5a ammeter




0-150v voltmeter

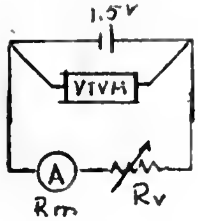
The arrangement of the resistors on the bread board was:




The probes were equipped with alligator clips for convenience. Wires equipped with spring clips were supplied to connect the various resistors to the terminals.

Circuits used in calibrating the meter:

0-15ma range

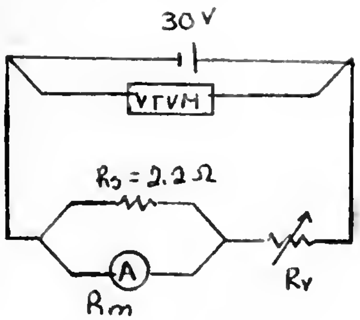



Total resistance of the circuit = $R_m + R_v$

$= 20 + R_v$

Note: If $R_v$ is less than 100Ω, the current will be greater than 15ma and the meter might be damaged.

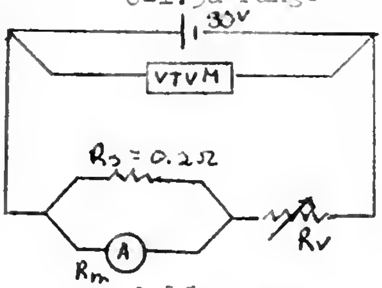
0-150 ma range




Because there is a 2.2Ω resistor in parallel with the meter resistance, the total resistance of the circuit is $R_v + R_{eq}$ where $R_{eq}$ is the equivalent resistance of the parallel arrangement =

$$\frac{R_m R_s}{R_m + R_s} = \frac{44}{22.2} = 2\,\Omega. \qquad R_t = R_v + 2\Omega.$$

0-1.5a range

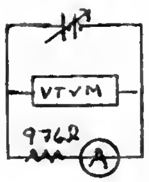



Again, $R_t = R_v + R_{eq}$

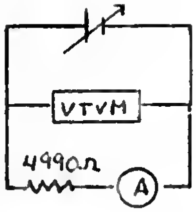
$$R_{eq} = \frac{R_m R_s}{R_m + R_s} = \frac{4}{20.2} = 0.2\,\Omega.$$

$R_t = R_v + 0.2\Omega.$

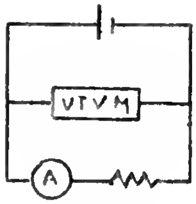
0-15v range



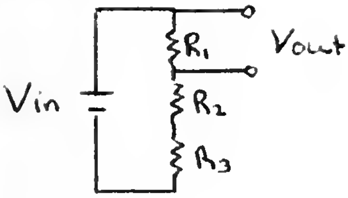
0-75v range




0-150v range




Because a voltage divider depends on the relative voltage drop across resistors, changing the current through these resistors will change the voltage drop.




In the case of the divider at left, $V_{out} = \frac{R_1}{R_2 + R_3 + R_1} V_{in}$. If, however, the output resistance is not infinite, there will be, in effect, a finite resistance in parallel with $R_1$ and the effective resistance would no longer be $R_1$. Therefore, by drawing current in the output circuit, the value of the output voltage is changed. However, in the calibration of the meter, we are not interested in the absolute value of the voltage, only in the difference in readings between a VTVM and the multimeter. If both are therefore connected across the voltage divider, the voltage drop across each will be the same, even though the drop across the divider changes.

The above equation may be derived from Ohm's law:

$$V_{in} = iR_1 + iR_2 + iR_3$$

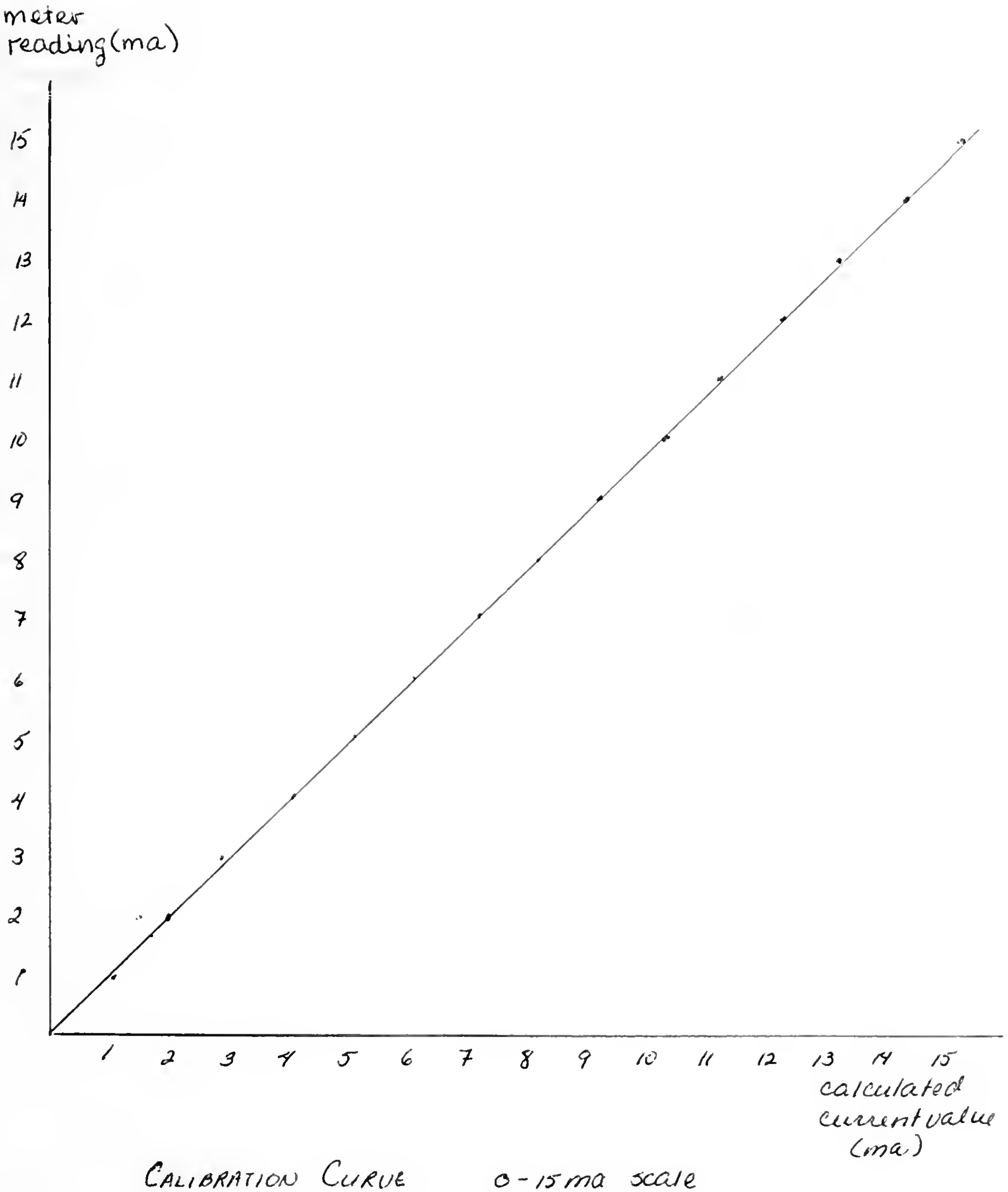
$$V_{out} = iR_1$$

$$\frac{V_{out}}{V_{in}} = \frac{iR_1}{i(R_1 + R_2 + R_3)}$$

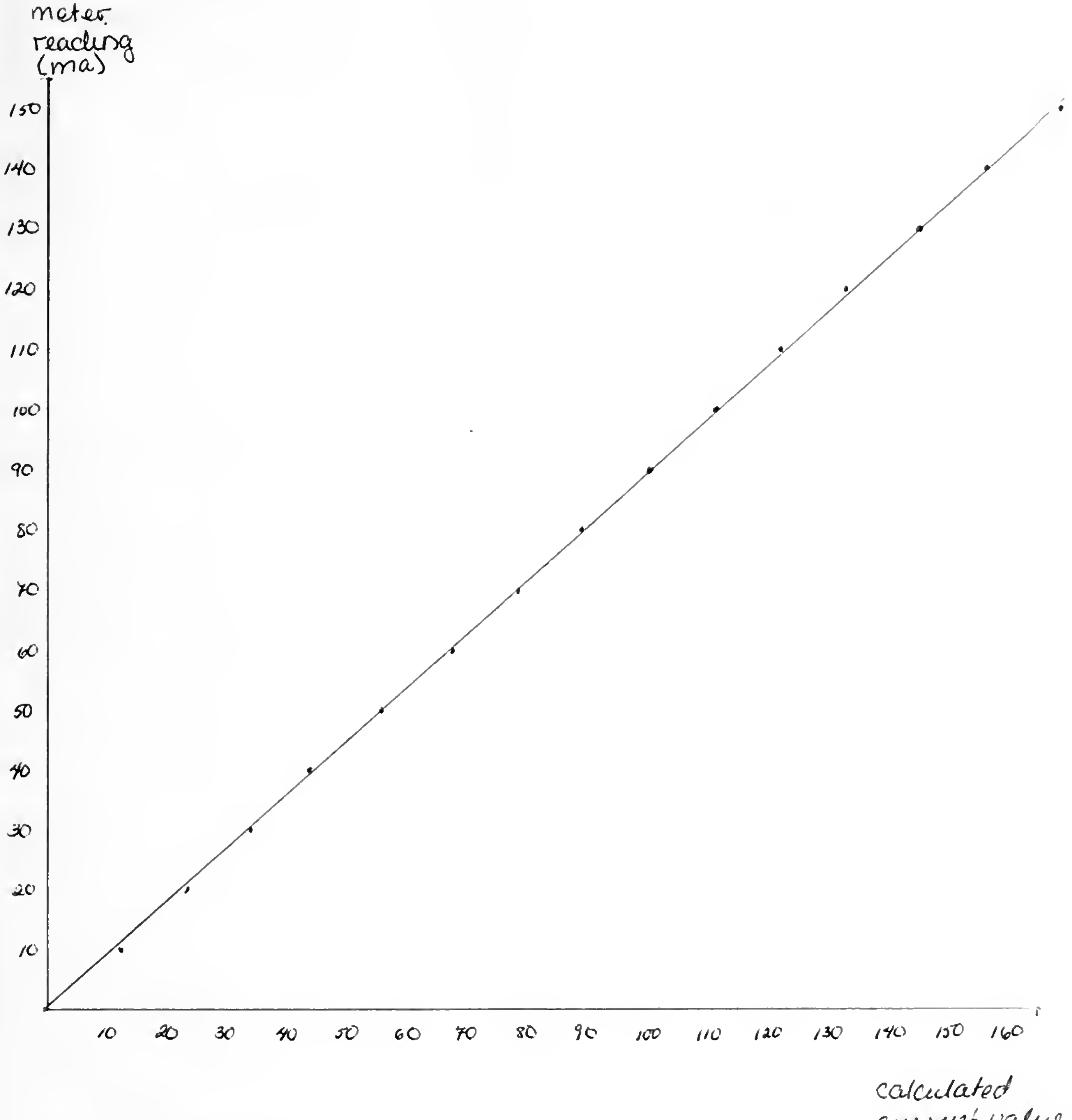
$$V_{out} = \frac{R_1}{R_1 + R_2 + R_3} V_{in}.$$

Data - calibration of the 0-15ma scale and the 0-150ma scale

| Meter reading (ma) | Voltage (volts) | Resistance of decade box ( ) | Current in circuit (calculated - ma) |
|---|---|---|---|
| 1.0 | 1.5 | 1320 | 1.12 |
| 2.0 | 1.5 | 730 | 2.0 |
| 3.0 | 1.5 | 490 | 2.95 |
| 4.0 | 1.5 | 350 | 4.05 |
| 5.0 | 5.0 | 980 | 5.0 |
| 6.0 | 5.0 | 800 | 6.1 |
| 7.0 | 5.0 | 684 | 7.1 |
| 8.0 | 5.0 | 589 | 8.2 |
| 9.0 | 5.0 | 524 | 9.2 |
| 10.0 | 5.0 | 473 | 10.2 |
| 11.0 | 5.0 | 426 | 11.2 |
| 12.0 | 5.0 | 386 | 12.3 |
| 13.0 | 5.0 | 356 | 13.2 |
| 14.0 | 5.0 | 328 | 14.4 |
| 15.0 | 5.0 | 306 | 15.3 |
| | | | |
| 10.0 | 30.5 | 2400 | 12.7 |
| 20.0 | 30.5 | 1300 | 23.5 |
| 30.0 | 30.5 | 890 | 34.2 |
| 40.0 | 30.5 | 690 | 44.2 |
| 50.0 | 30.5 | 550 | 55.2 |
| 60.0 | 30.5 | 450 | 67.5 |
| 70.0 | 30.5 | 390 | 73.0 |
| 80.0 | 30.5 | 340 | 89.0 |
| 90.0 | 30.5 | 302 | 100.0 |
| 100.0 | 30.5 | 272 | 111 |
| 110. | 30.5 | 249 | 122 |
| 120 | 30.5 | 22[illegible] | 133 |
| 130 | 30.5 | 205 | 145 |
| 140 | 30.5 | 194 | 156 |
| 150 | 30.5 | 180 | 169 |




CALIBRATION CURVE  0-15 ma scale




CALIBRATION CURVE 0-150 ma scale

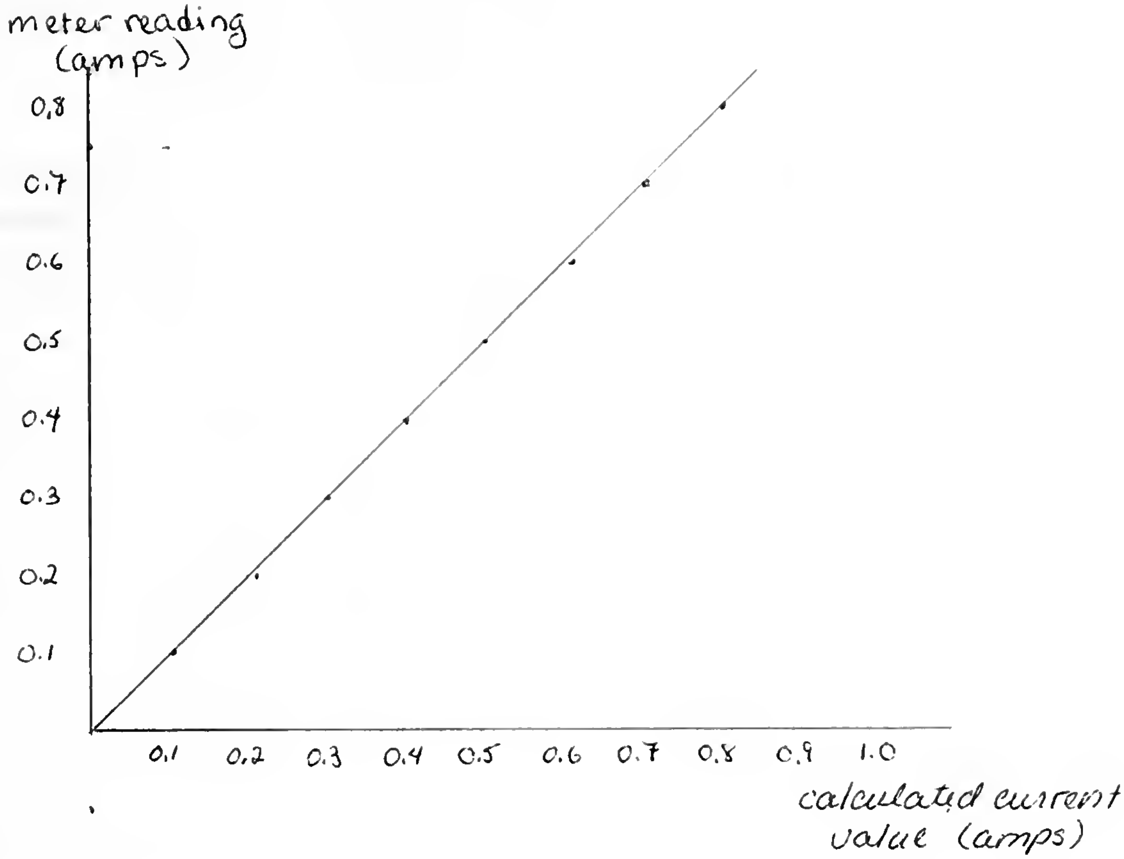
Data - calibration of the 0-1.5a scale

| Meter reading (amps) | Voltage (volts) | Resistance of decade box (ohms) | Current in circuit (Calculated - amps) |
|---|---|---|---|
| 0.10 | 30.5 | 300 | 0.102 |
| 0.20 | 30.5 | 150 | 0.215 |
| 0.30 | 30.5 | 99 | 0.308 |
| 0.40 | 30.5 | 74 | 0.410 |
| 0.50 | 30.5 | 60 | 0.505 |
| 0.60 | 30.5 | 49 | 0.62 |
| 0.70 | 30.5 | 42.1 | 0.72 |
| 0.80 | 30.5 | 36.9 | 0.82 |

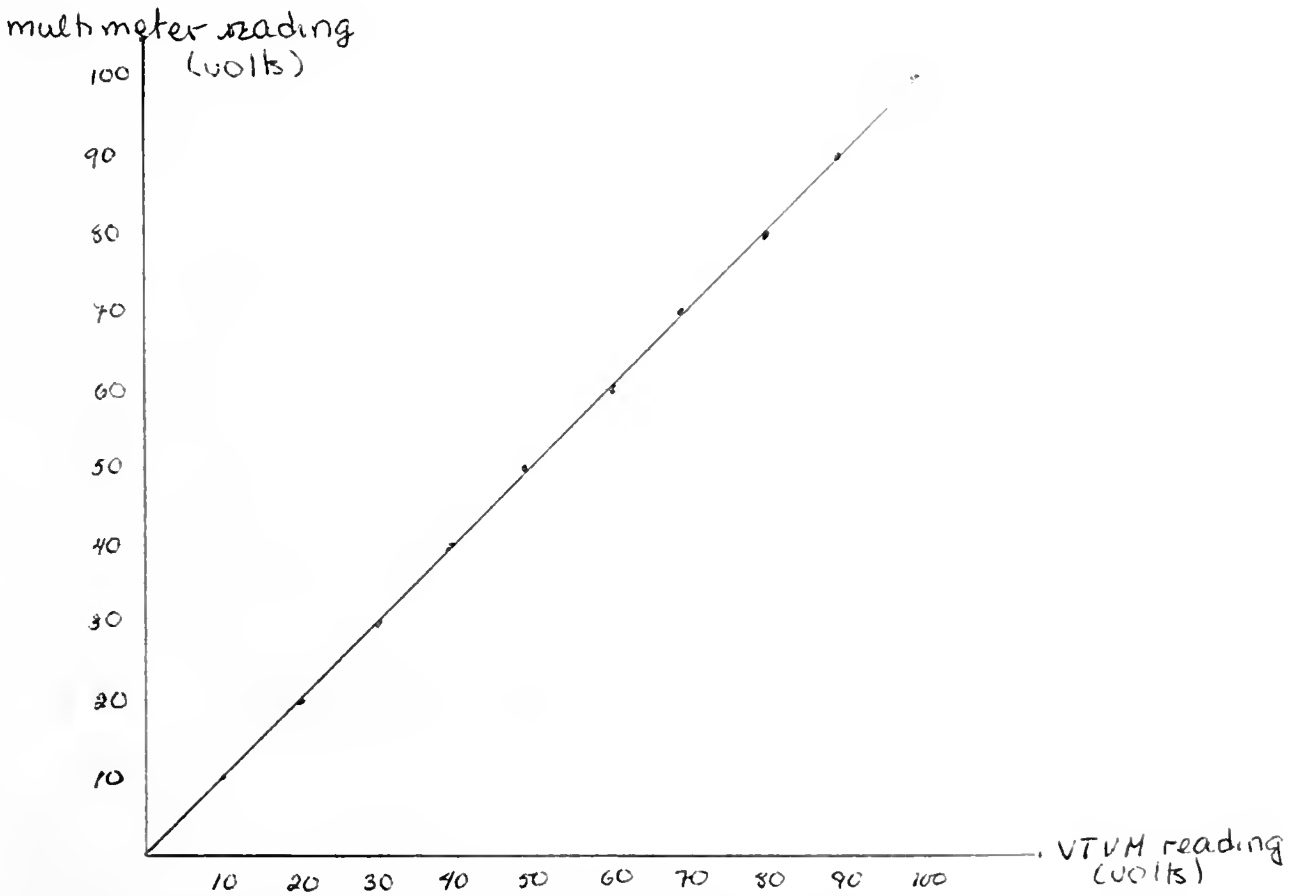
Although the ammeter will measure higher currents, these would be too large for the resistors of the decade box, so further readings were not taken.

Data - calibration of voltmeter scales

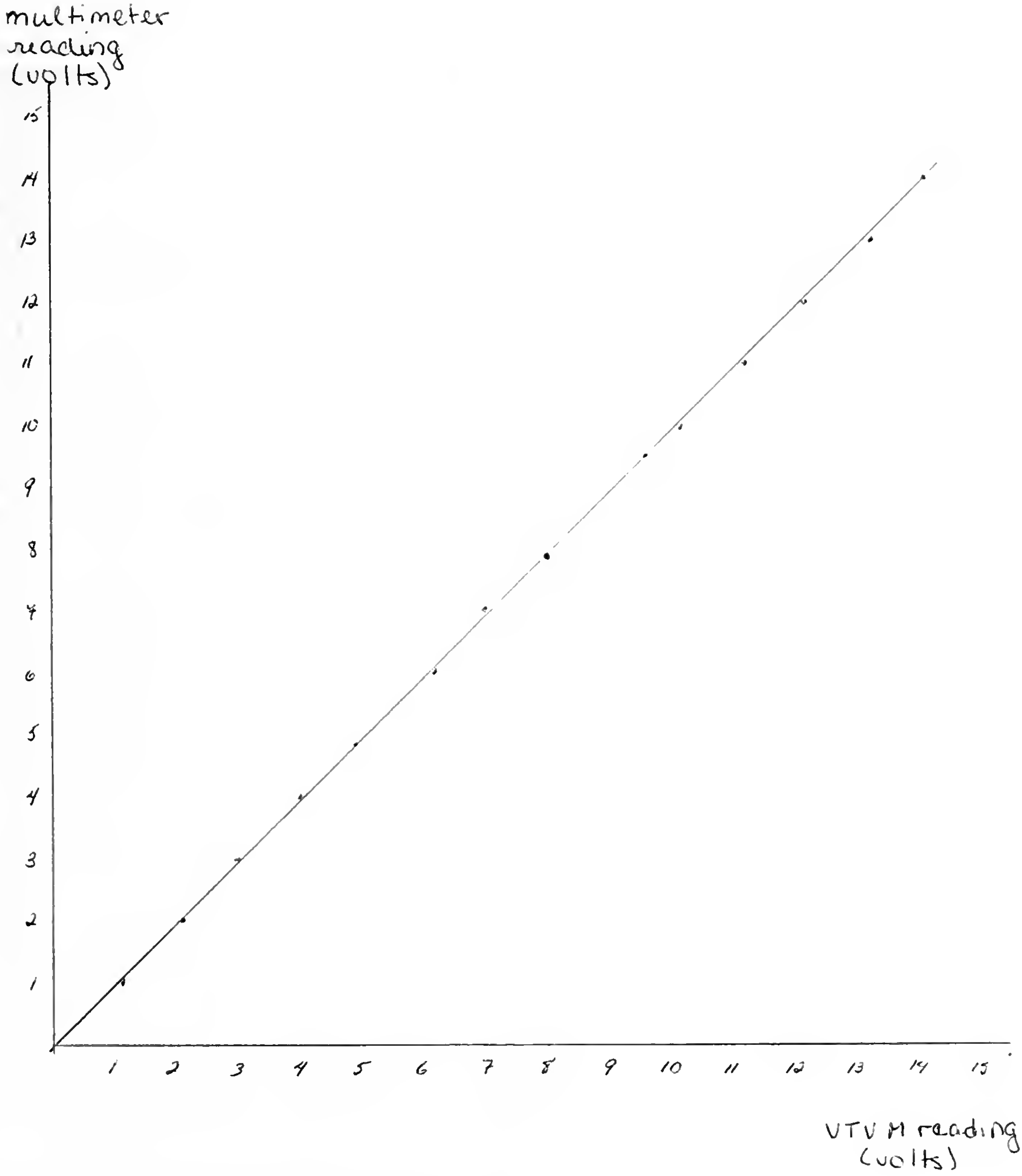
| 0-15v range | | 0-75v range | | 0-150v range | |
|---|---|---|---|---|---|
| Multimeter reading (v) | VTVM reading (v) | Multimeter reading (v) | VTVM reading (v) | Multimeter reading (v) | VTVM reading (v) |
| 1.0 | 1.1 | 5.0 | 4.8 | 10 | 10 |
| 2.0 | 2.1 | 10.0 | 10.0 | 20 | 20 |
| 3.0 | 3.0 | 15.0 | 14.9 | 30 | 30 |
| 4.0 | 4.0 | 20.0 | 20.0 | 40 | 39 |
| 4.9 | 4.9 | 25.0 | 25.0 | 50 | 49 |
| 6.0 | 6.2 | 30.6 | 30.0 | 60 | 60 |
| 7.0 | 7.0 | 35.0 | 35.1 | 70 | 69 |
| 7.9 | 8.0 | 40.0 | 40.1 | 80 | 80 |
| 9.5 | 9.6 | 45.0 | 45.0 | 90 | 89 |
| 10.0 | 10.2 | 50.0 | 50.0 | 100 | 99 |
| 11.0 | 11.2 | 55.6 | 54.0 | | |
| 12.0 | 12.2 | 65.0 | 64.5 | | |
| 13.0 | 13.3 | 70.0 | 70.0 | | |
| 14.0 | 14.1 | 75.0 | 74.5 | | |



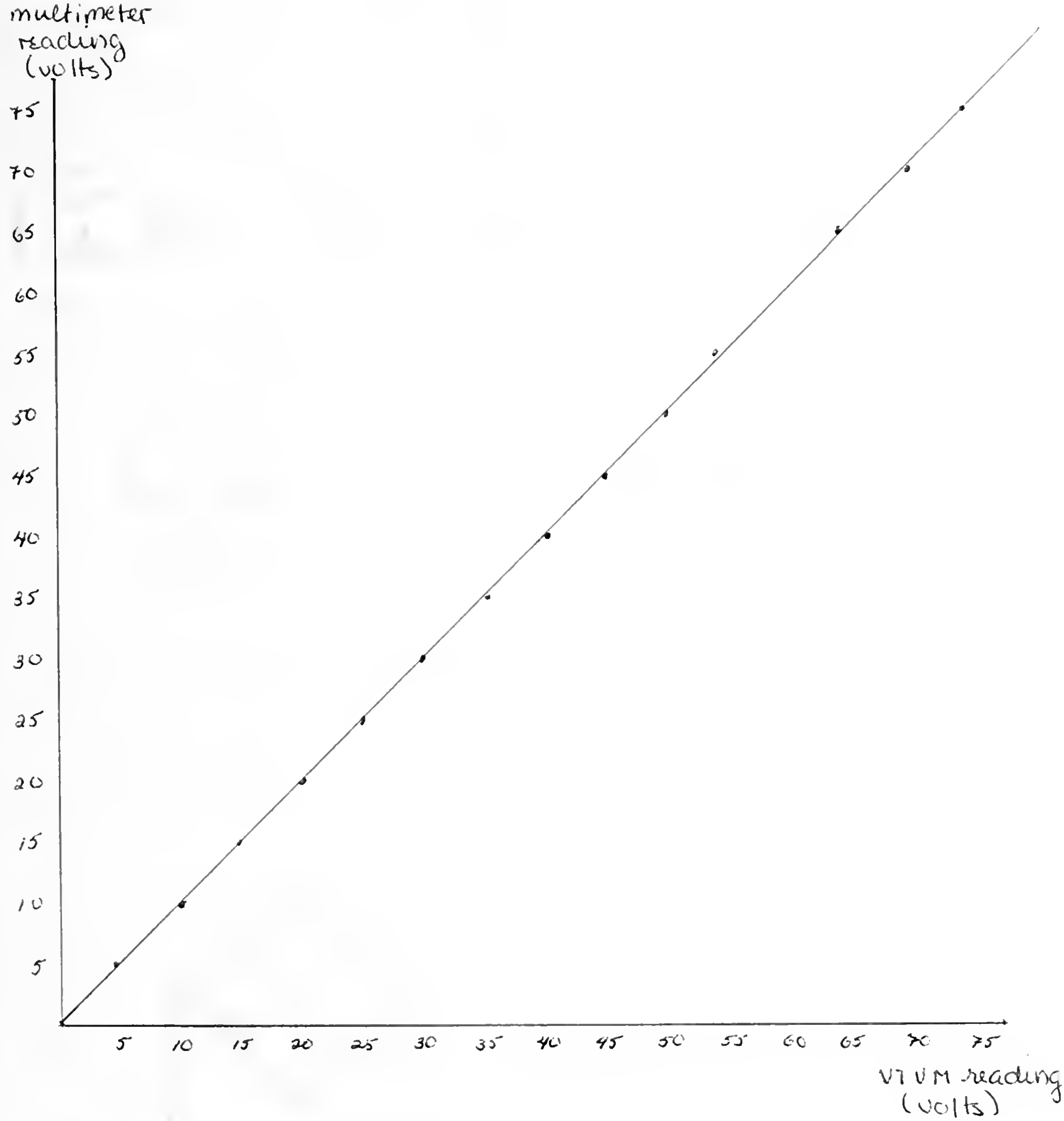

CALIBRATION CURVE 0-1.5a scale




CALIBRATION CURVE 0-150 VOLT scale




CALIBRATION CURVE 0-15 volt scale




CALIBRATION CURVE 0-75V scale

## NULL BALANCE DEVICES: THE WHEATSTONE BRIDGE AND THE POTENTIOMETER

It has been shown that a D'Arsonval type meter may be used to measure both potentials and currents. The problem of resistance measurements is not as easy. To use Ohm's law, one must apply a potential across the resistor and then measure the current through it. If one has available a constant source of known potential, one may use the following circuit (Figure 12);

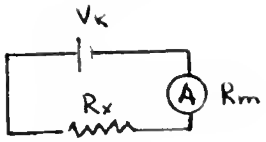



Figure 12

$V_k$ is the known potential, $R_x$ the unknown resistor, and $R_m$ is the resistance of the ammeter. Because $V_k = i(R_x + R_m)$, it is possible to calculate $R_x$ if $R_m$ is known, but there is no simple linear scale that may be read directly because of the meter resistance. There is also the problem of knowing the voltage accurately. Often two meters are used:

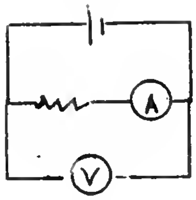



Figure 13

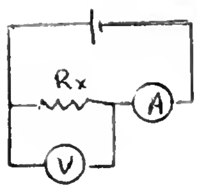



Figure 14

In the circuit shown in Figure 13, the above problem is not eliminated, and in Figure 14, only part of the current in the ammeter flows through $R_x$, some also flows through the voltmeter.

Resistances may be measured accurately by use of the null balance Wheatstone Bridge:

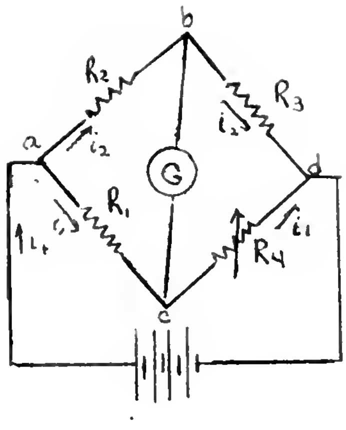



Figure 15

Here the detector is a galvanometer. The bridge is balanced by adjusting the resistors until there is no current through the galvanometer. If there is no current through the galvanometer, then there can be no potential difference across the galvanometer and points b and c must be at the same potential. In order for this to be true, the voltage drop across $R_1$ must equal the voltage drop across $R_2$, ie, $V_{ab} = V_{ac}$. Also,

since no current flows through the galvanometer, the current in $R_2$ must equal the current in $R_3$ and the current in $R_1$ must equal the current in $R_4$. Now, $V_{ab} = i_2R_2$ and $V_{ac} = i_1R_1$. Therefore, $i_1R_1 = i_2R_2$. By similar arguments, $V_{bd} = V_{dc}$, and $i_1R_4 = i_2R_3$. Dividing the two equations, one obtains:

$$\frac{R_1}{R_4} = \frac{R_2}{R_3} \quad \text{or} \quad \frac{R_1}{R_2} = \frac{R_4}{R_3}$$

If $R_3$ is an unknown resistor, and $R_1$, $R_2$ and $R_4$ are known, the value of $R_3$ is readily calculated.

A very convenient Wheatstone Bridge may be constructed using a decade box for $R_4$ and varying the ratio of $\frac{R_1}{R_2}$ in a simple manner. If $R_1:R_2 = 1:1$, then $R_3:R_4 = 1:1$ and the value of the unknown resistance, $R_3$, will be that of the decade box. If $\frac{R_1}{R_2} = \frac{10}{1}$, then the unknown resistande will have a value ten times as great as the value of the resistance of the decade box when the bridge is balanced.

Another null balance instrument is the potentiometer. This may be used to measure potential differences more accurately than a voltmeter since no current need be drawn.

If two equal potential sources are connected in such a way as to oppose one another, no current can flow in the circuit because there is no potential difference between any two points in the external circuit.

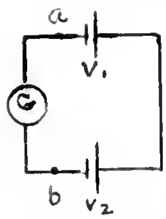



Figure 1

If $V_1 = V_2$, then points a and b afe at the same potential and no current flows through the galvanometer.

If an unknown voltage is opposed by a known, variable voltage, and this known voltage is adjusted until no current flows between the two potential sources, then the unknown voltage is equal to that known voltage. In this way the voltage is measured without drawing any current from the variable voltage source when the potentiometer is balanced. Therefore, a voltage divider can be used to vary the voltage. A simple potentiometer is shown in Figure 17.

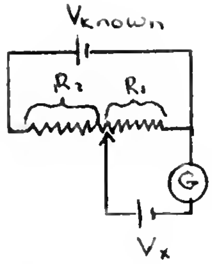



Figure 17

The resistance is adjusted until no current flows through the galvanometer. $V_x$ must then equal the voltage drop across $R_1$ which is $iR_1$. But $i = \frac{V_{known}}{R_1 + R_2}$ so

$$V_x = iR_1 = \frac{R_1 V_{known}}{R_1 + R_2} \quad .$$

The accuracy of this potentiometer is dependent upon the accuracy with which the voltage is known and the accuracy with which the ratio of $R_1$ to the sum of $R_1 + R_2$ can be determined. This type of potentiometer is also inconvenient because calculations must be made for every measurement.

A more convenient potentiometer is one in which the current through the voltage divider is adjusted by use of a standard cell so that the voltage across the divider is known accurately. If the divider is carefully designed, it is possible to know how many volts are across each div[illegible]n and thus the voltage can be read directly without having to calculate each time. The Leeds and Northrup Student Potentiometer is this kind of potentiometer.

This potentiometer uses 16 ten-ohm resistors in series. 15 of these are precision resistors, the 16th is a slide wire which has been calibrated to allow further divisions. The circuit used to standardize this is represented in Figure 18.

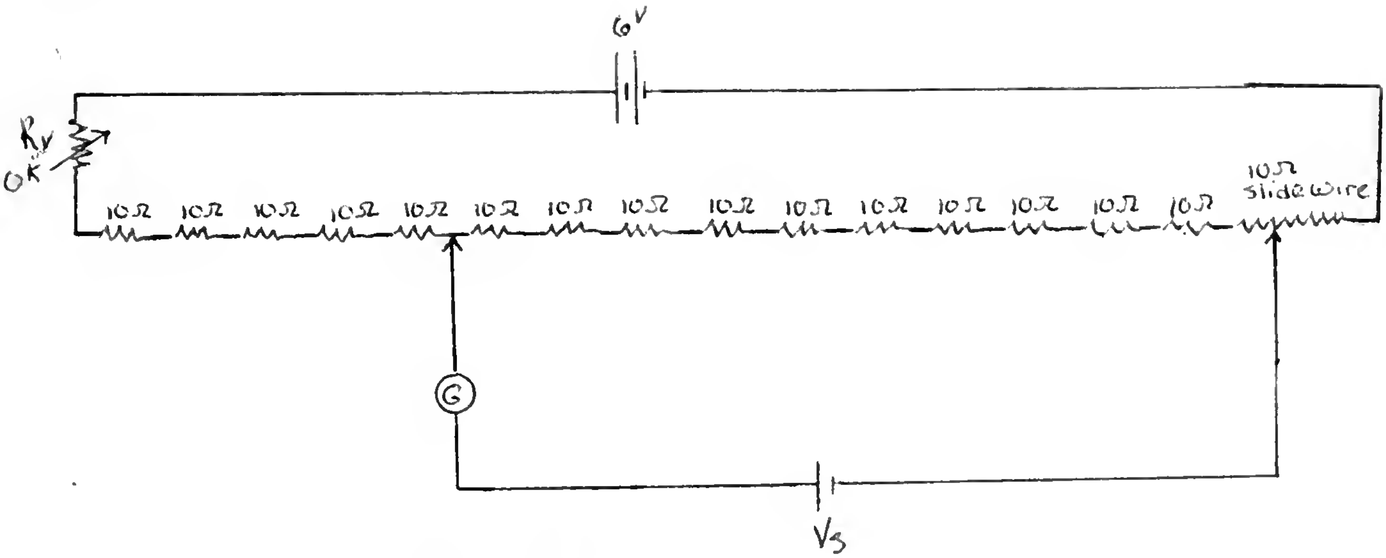
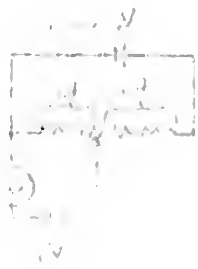



Figure 18



If $V_s$, the standard cell, is known to have a potential of 1.0190v, then this voltage is set on the potentiometer by using ten of the ten-ohm resistors and $\frac{19}{100}$ of the length of the slide wire resistor (the resistance of the slide wire is proportional to its length). $R_v$ is then adjusted until no current flows through the galvanometer. The voltage drop across $100\Omega + \frac{19}{100} \cdot 10\ \Omega$ or $1019\ \Omega$ is 1.019 volts and the drop across each ten-ohm resistor or division of the potentiometer is 0.1v. If the 6v battery remains constant and $R_v$ is not changed, then each division will represent 0.1v and a very accurate, conveinent potentiometer is available. If the external circuit is arranged with a double throw, double pole switch, the standard cell may easily be put back in the circuit from time to time to verify the standardization of the potentiometer (see Figure 22).

The Student Potentiometer also has a multiplier device which allows one to measure voltages which are $\frac{1}{100}$ that of the standard cell with the same degree of accuracy. This is essentially just a shunting circuit which makes it possible for only $\frac{1}{100}$ of the voltage drop to appear across the voltage divider. If 1. volts are applied across the circuit shown in Figure 19, $R_2$ being the voltage divider and $R_1$ being a standard resistor, each division of of $R_2$ will have 0.1 volts across it.

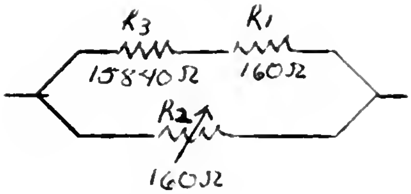



Figure 19

If, while taking measurements, the positions of $R_1$ and $R_2$ are reversed as illustrated in Figure 20, 1.6 volts still appear across the circuit but now the voltage dfop across $R_2$ is only $\frac{160}{16000}(1.6)$ or 0.016 volts, and the voltage drop across each division is only 0.001v or 1mv.

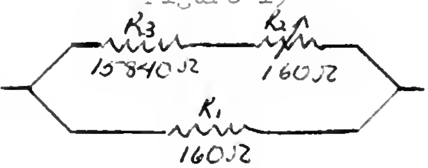
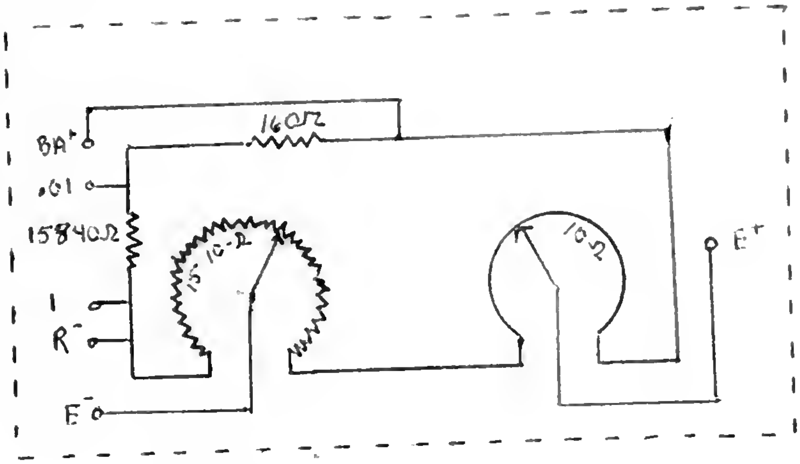



Figure 20

The circuit diagram for the Leeds and Northrup Student Potentiometer is shown in Figure 21.




The 15 ten-ohm resistors and the slide wire resistor are arranged in a circle to save space.

Figure 21

Figure 22 shows the potentiometer connected for voltage measurements.

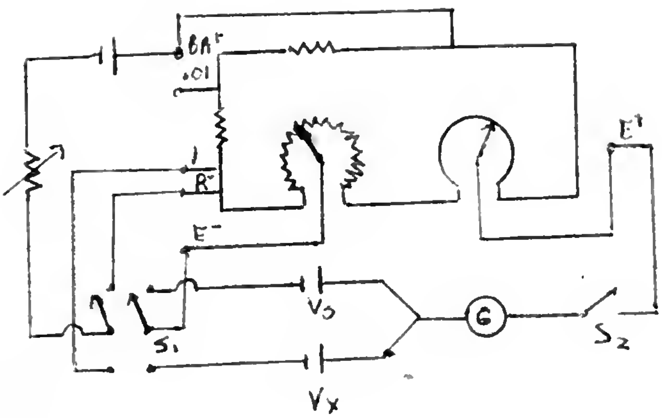



Figure 22

The galvanometer used in the following experiments is the Leeds and Northrup 2420-a galvanometer with an external damping and shunt resistor. The theory of these resistors may be found in Sears' Electricity and Magnetism, chpt 10. The circuit is illusrrated in Figure 23.

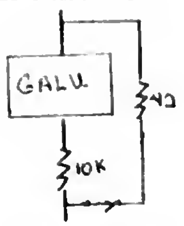



Figure 23

This will be represented simply as

throughout the experiments

Procedure

The bread board circuit available for the Wheatstone Bridge is illustrated by Figure 24. The decade box has a range from 0-999 Ω. The smallest divisions on the box are 0.1 Ω, but these are not accurate any more.

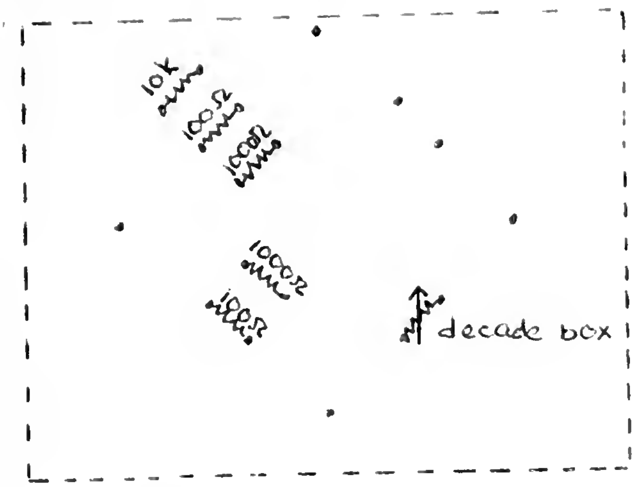



Figure 24

Show how you would connect the bridge (using a dry cell as the voltage source) to give the following resistance ranges with three significant figures: 100-999 Ω; 10.0-99.9 Ω; 1000-9999 Ω; and 10000-99999 Ω.

Measure the resistances of several unknown resistors.

Potentiometers and chemical cells

The multimeter, a slide wire potentiometer, and the Leeds and Northrup Student Potentiometer will be used to determine the value of several chemical cells. For further information about chemical potentials and the Weston Standard cell, the student is referred to a standard chemistry text such as Meites and Thomas' Advanced Analytical Chemistry.

Measure the potential of a dry cell (1.5v) with the multimeter. Then use the slide wire potentiometer in the following circuit:

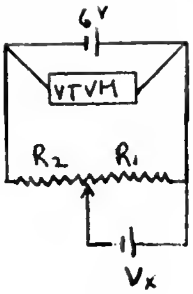



Figure 25

Because the length of the wire is proportional to the resistance, the ratio of $R_1$ to $R_1 + R_2$ is the ratio of $L_1$ to $L_1 + L_2$ where $L_1$ and $L_2$ are the lengths of $R_1$ and $R_2$ respectively. Use the VTVM to measure the voltage across the slide wire. Why should this

be kept across the wire when the bridge is being balanced?

Use a standard Weston Cell as $V_s$ and connect the Leeds and Northrup potentiometer as shown in Figure 22. Set the potentiometer to read the potential of the standard cell and adjust $R_v$ until the bridge is balanced. $S_2$ should be a tap switch and should be held down as briefly as possible to avoid drawing much current from the standard cell. Then measure the voltage of the dry cell with this potentiometer.

Using battery cups, set up the following chemical cells:

$Cu | Cu(NO_3)_2(1M) \| Zn(NO_3)_2(1M) | Zn$

$Ag | AgNO_3(1M) \| Cu(NO_3)_2(1M) | Cu$

$Ag | AgNO_3(1M) \| Zn(NO_3)_2(1M) | Zn$

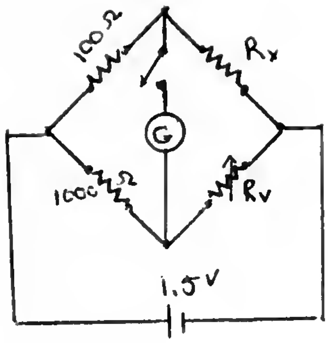
Measure the potential of each cell, determine which electrode is positive and which is negative, and write the half cell reactions. On this basis, choose the most convenient ion as a standard and establish a relative scale of half cell potentials.

Then dilute part of the $Cu(NO_3)_2$ solution to 0.001M and measure the potential of a $Cu | Cu(NO_3)_2(1M) \| Cu(NO_3)_2(0.001M) | Cu$ cell. Predict which electrode will be negative.

Find a potentiometric titration in one of the laboratory manuals and do it using either the Student Potentiometer or the Beckman Model G pH meter. (This pH meter is just an instrument in which the low potential of the glass esectrode is amplified and then measured with a potentiometer which is calibrated in pH units instead of volts and is standardized with a buffer solution of some pH value instead of with a standard voltage.)

Calculations, data and conclusions

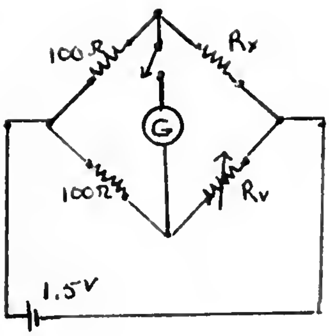
Wheatstone Bridge circuits:



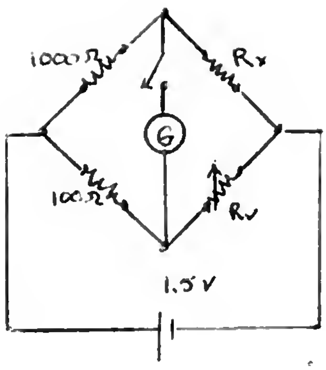

$$\frac{100}{1000} = \frac{R_x}{R_v} \quad ; \quad R_x = \frac{1}{10}R_v$$

Since the decade box must be used from 100Ω to 999Ω to give sufficient accuracy, this range is multiplied by 1/10 to give a range of 10Ω to 99.9Ω.

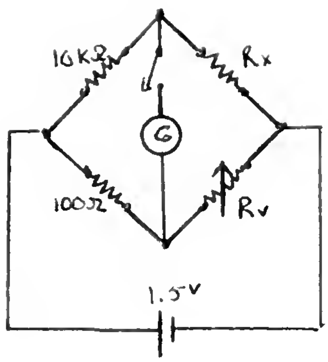
For range of 10.0Ω to 99.9Ω




100Ω to 999Ω range

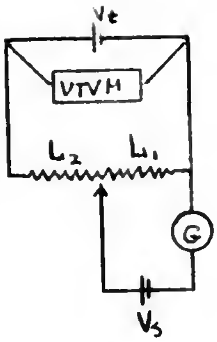



1000Ω to 9990Ω range




10000Ω to 99900Ω range

The slide wire potentiometer was used to measure the potentials of two different Weston cells.



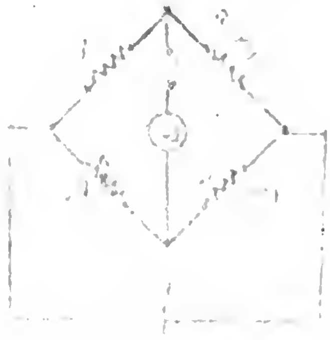

| Data: | $V_t$ | $L_1$ | $L_1 + L_2$ |
|---|---|---|---|
| Cell A | 6.3v | 13.9 | 100.0 |
| Cell B | 6.4v | 14.0 | 100.0 |

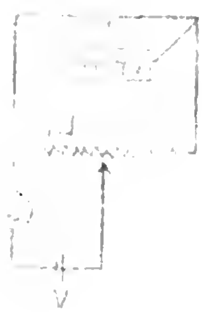
Calculations:

Cell A $\quad V_A = \dfrac{V_t L_1}{L_1 + L_2} = \dfrac{13.9}{100}(6.3) = 0.87\text{v}$

Cell B $\quad V_B = \dfrac{V_t L_1}{L_1 + L_2} = \dfrac{14}{100}(6.4) = 0.90$

The potential of a new standard Weston cell is 1.0186v. Because of a calculation





error, Cell 3 was thought to be accurate enough, and its voltage was taken to be 1.0190v during the rest of the experiment.

Cell potentials

The slide wire poteniometer and multimeter were only used in the measurement of the potential of the first cell.

Data:

| Cell | Leeds and Northrup Potentiometer | Slide wire potentiometer | Multimeter | negative electrode |
|---|---|---|---|---|
| copper - zinc | 0.9270v | 0.95v | 0.6v | zinc |
| silver - copper | 0.4150v | - | - | copper |
| silver - zinc | 1.4440v | - | - | zinc |

Because the copper electrode was at a higher potential than the zinc electrode and at a lower potential than the silver electrode, the copper half cell, $Cu^{++} + 2e^{-} \rightleftharpoons Cu$, was taken as the reference potential and assigned a value of zero volts.

In the first cell, copper was plated out while zinc was ionized and dissolved in the solution. The total reaction was therefore : $Cu^{++} + Zn \rightarrow Zn^{++} + Cu$. By convention, a reaction which occurs spontaneously has a total potential which is positive. Since the copper half cell is defined to have a potential of zero volts, the half cell, $Zn \rightarrow Zn^{++} + 2e^{-}$, must have a potential of +0.927v. The reverse reaction, $Zn^{++} + 2e^{-} \rightarrow Zn$, would therefore have a potential of -0.927v.

In the second cell, copper was the negative electrode which indicates that the reaction at that electrode was $Cu \rightarrow Cu^{++} + 2e^{-}$ (leaving the electrons on the electrode, thus making it negative). The silver was plated out: $Ag^{+} + e^{-} \rightarrow Ag$. The total reaction had a potential of 0.415v, and since the copper half cell has a potential of zero volts, the silver half cell must have a potential of 0.415v.

Therefore the following arrangement can be made:

| | |
|---|---|
| $Zn^{++} + 2e^{-} \rightleftharpoons Zn$ | -0.927v |
| $Cu^{++} + 2e^{-} \rightleftharpoons Cu$ | 0.00v |
| $Ag^{+} + e^{-} \rightleftharpoons Ag$ | +0.415v |

On this basis, the reactions which would be expected to go spontaneously in a zinc - silver cell are: $Zn \rightarrow Zn^{++} + 2e^{-}$ and $Ag^{+} + e^{-} \rightarrow Ag$. The total

potential would be expected to be 1.342v with zinc as the negative electrode. The measured potential was 1.444v and zinc was indeed the negative electrode. The discrepancy in values could have been due to differences in concentrations, temperature even the battery cups, and demonstrates the difficulty in determining absolute cell potentials.

A cell was made using copper electrodes in copper solutions of two different concentrations, one which was 1M in $Cu^{++}$ and one which was 0.001M in $Cu^{++}$. Because at equilibrium the $Cu^{++}$ concentration should be equal in the two solutions, copper should be plated out of the 1M solution and it should be dissolved into the 0.001M solution, making the electrode in the less concentrated solution the negative electrode. This was found to be the case. The potential difference was found to be 0.0575v which, from the Nernst equation, is seen to be in the right range.

$$E = \frac{.059}{2}(\log 10^3) = \frac{3}{2}(.059) = .088v$$

From the preceding work, the student should have enough understanding to be able to follow the electrogravimetric and polarographic methods which may be found in any analytical text. These are the experimental methods which should be used next, but since they are treated adequately in other sources, they will not be discussed here.

## CAPACITORS, INDUCTORS, AND AC CIRCUITS

In this section it is assumed that the student knows what an ac current is, the equations for instantaneous and rms values, and what each means, and how ac detectors (including the oscilloscope) work. Supplement III in Malmstadt and Enke's Electronics for Scientists may be of value and chapter 1 of that book has a very good discussion on detectors. Chapter 2 in Brophy's Basic Electronics for Scientists is also a good reference for this section with an excellent treatment of oscilloscopes.

The purpose of the discussion in this section is to clarify the effects of capacitors and inductors in ac circuits so that their use in electronics may be understood.

### Capacitors

A capacitor is an electrical component which has the ability to store charge. The voltage which appears across a capacitor is proportional to the charge on it. The proportionality constant, C, is the capacitance of the capacitor. $Q = CV$ where Q is the charge on the capacitor and V is the voltage.

If a capacitor is placed in series with a resistor and a dc voltage is applied, current will flow until the voltage across the capacitor is equal to the voltage applied. The charge on the capacitor at a given time may be found by considering the circuit shown in Figure 2.

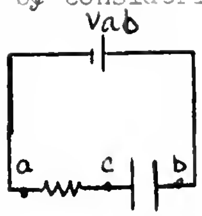



Figure 2.

$V_{ab} = V_{ac} + V_{cb} = iR + \frac{q}{C}$. But $i = \frac{dq}{dt}$

$\therefore V_{ab} = \frac{dq}{dt}R + \frac{q}{C}$. This differential equation may be solved to give

$$q = CV(1 - e^{-t/RC}).$$

The current, i, then becomes $\frac{d\ CV(1-e^{-t/RC})}{dt} = \frac{1}{RC}e^{-t/RC}$. As t approaches infinity, i approaches zero. The current at t = 0 is $\frac{1}{RC}$ and this decreases exponentially with time. When i=0, $V_{ac}$=0 and $V_{ab}=V_{bc}$ or all the voltage appears across the capacitor.

If the dc voltage is replaced by an alternating voltage, the situation becomes quite different. Initially there is no voltage drop across the capacitor. When voltage is applied, current flows through the circuit.. As long as it flows in one direction, the capacitor continues to charge and the voltage across it continues to increase. When the current reverses direction however, the capacitor begins to discharge. The voltage across the capacitor is therefore at a maximum when the current has reached zero, before it changes directions.

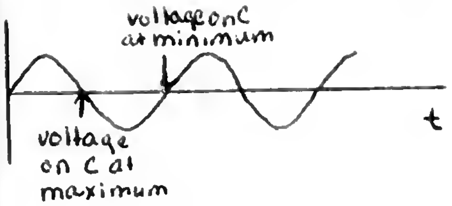


Figure 27

Before the voltage across the capacitor can be reversed, the capacitor must discharge completely and then, as long as current flows in the opposite direction, the capacitor will charge in that direction. The voltage across the capacitor will therefore be a minimum when the current has increased to zero again but before it changes directions. It then becomes apparent that half of the current flow in any one direction is used in removing the charge acquired by the capacitor in the previous half period, and the other half of the current flow is used to charge it in the new direction. Furthermore, the voltage reaches its maximum or minimum a quarter of a period after the current reaches its respective maximum or minimum. Therefore the current is said to lead the voltage by 90°. (See Figure 28)

This may be shown mathematically by considering the circuit of Figure 29.

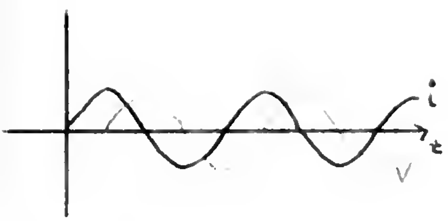


Figure 28

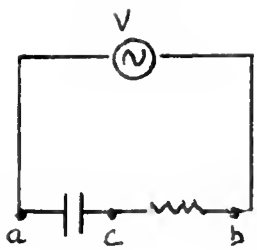


Figure 29

Since the components are in series with each other, the current through each component must be the same at any time, ∴ If $i$ is the instantaneous current and $I_p$ the peak current, then $i = I_p \sin 2\pi ft$.

$$V_{cb} = iR = RI_p \sin 2\pi ft$$

$$V_{ac} = \frac{q}{C} \qquad \text{Since } i = \frac{dq}{dt}, \quad q = \int i\,dt = \int I_p \sin 2\pi ft.$$

$$\therefore\ q = -\frac{I_p}{2\pi f}\cos 2\pi ft + \text{constant.} \quad \text{But } q=0 \text{ when the current is}$$

$$\text{a maximum or when } 2\pi ft = \frac{\pi}{2} \quad \therefore \text{ the constant} = 0.$$

$$q = -\frac{I_p}{2\pi f}\cos 2\pi ft \quad \text{and } V_{ac} = \frac{I_p}{2\pi fC}\sin(2\pi ft - 90°)$$

By analogy with the equation for the voltage across a resistor, a capacitor may be considered to have a resistance of $\frac{1}{2\pi fC}$ and cause the voltage to be 90° out of phase with the current. $\frac{1}{2\pi fC}$ is called the reactance of the capacitor and is denoted by $X_c$.

If a resistor and capacitor are connected in parallel with an ac voltage across them, the voltage across each will be the same at any given time but the currents through them will be 90° out of phase.

## Inductors

An inductor is a coil of wire. In a dc circuit, this will be an electromagnet and after the current reaches a maximum, any voltage across it will be due to the iR drop. In an ac circuit, however, the constantly changing current induces an emf in the coil. To see why this emf is induced, let us consider the properties of a charge moving in a magnetic field.

A moving charge has associated with it a magnetic field. If this charge is moving in a magnetic field which is at right angles to the direction of its motion, it will experience a force which is mutually perpendicular to the velocity vector v and the field vector B. This may be understood by considering a positive charge moving as shown in Figure 30, through a magnetic field which is directed into the paper.

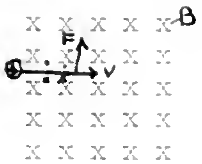



Figure 30

By the right hand rule, the field associated with the charge is seen to augment the field on one side and reduce it on the other, causing a gradient in the field. The charge will therfore experience a force towards the top of the page.

If a conductor is moving in such a field, the free electrons will experience a force in the opposite direction, and a potential difference will develop in the conductor (see Figure 31). If the circuit is completed by sliding the wire along a u-shaped conductor as shown in Figure 32, current will flow in the circuit because of the potential developed as long as the wire is moving within the magnetic field. The current flowing through the wire has a magnetic field associated with it which again augments the existing field on one side and reduces it on the other; this time in such a way as to cause a force which opposes the motion of the wire.

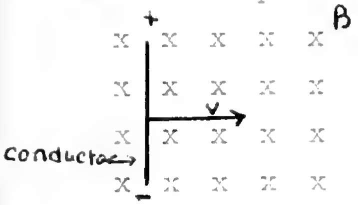


Figure 31

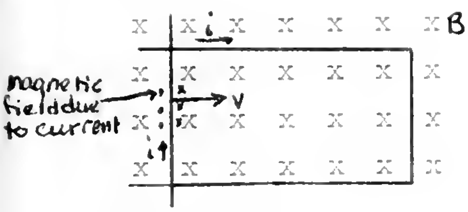


Figure 32

Another way to look at this is to say that the magnetic field is moving with respect to a stationary charge. The motion of the charge is relative, so if the magnetic field is moving, current will flow if there is a completed circuit.

If one considers a coil of wire, moving a bar magnet into the coil has the same effect as moving the coil around the magnet. If the coil is part of a complete circuit, current will flow such that the motion of the magnet is opposed by the field associated with the current. Since like fields repel one another, the coil must have a current induced such that the resulting electromagnet has its north pole opposite to the north pole of the magnet. The direction of such a current may be detemined by the right hand rule and will be in the direction indicated in Figure 33. In order for current to flow, there must be an emf induced, the direction of which is also indicated in Figure 33. Similarly, when the magnet is removed from the

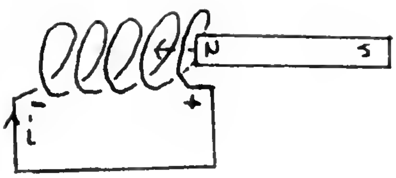


Figure 33

coil, a field would again be established to oppose the motion of the magnet. This time the direction of the induced field would be such that the south end of the coil would attract the north end of the magnet. Therefore, the current and enduced emf would be in the opposite direction.

Any change of the magnetic field within a coil therefore induces an emf which opposes the changing of the field. In an ac circuit, where the current through a coil is constantly changing, the magnetic field in the coil is also changing and therefore an emf is induced to oppose this change.

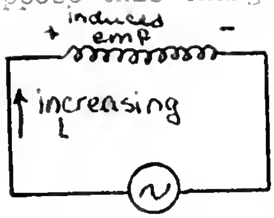



Figure 34

As the current through the coil increases, the magnetic field increases. If the current is increasing in the direction indicated in Figure 34, then an emf develops across the inductor which opposes this increase in current. This emf is greatest when the rate of change of the magnetic flux is greatest. This rate of change is directly proportional to the rate of change of the current. When i, still flowing in the direction indicated, begins to decrease, the field of the coil begins to decrease, and this decrease is opposed by inducing an emf in the opposite direction.

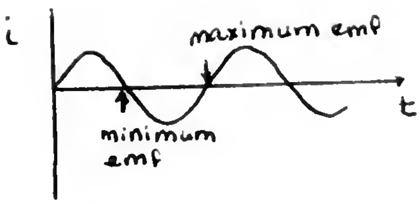



Figure 35

The induced emf, $V_L$, is proportional to the rate of change of the current. $V_L = L\frac{di}{dt}$ where L is the proportionality constant and is called the inductance.

The instantaneous current, i, in the circuit of Figure 36 is the same through the resistor and through the inductor. $i = I_o \sin 2\pi ft$. The voltage across R at any time is $V_R = RI_o \sin 2\pi ft$. The voltage across L $= L\frac{di}{dt} = LI_o 2\pi f \cos 2\pi ft = 2\pi fLI_o \sin(90° - 2\pi ft)$. The voltage across an inductor then leads the current by 90°. Again, by analogy with the voltage across R, the inductor may be considered to have a resistance of $2\pi fL$ and cause

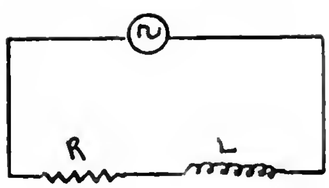
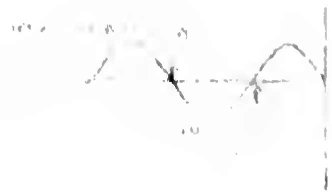
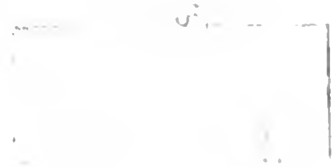



Figure 36





the voltage to be 90° out of phase with the current. $2\pi fL$ is called the reactance of the inductor and is denoted by $X_L$.

In the case of an inductor and a resistor connected in parallel, the voltage across each must be the same at any time, but the currents through them will be 90° out of phase with one another.

Resonance

If an inductor, capacitor and resistor are all connected in series, the current through each will be the same at any time, but the voltages across each will be out of phase.

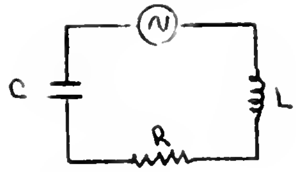


Figure 37

The voltage across R, $V_R$, = $RI_p \sin 2\pi ft$

The voltage across L, $V_L$, = $2\pi fLI_p \sin(90° - 2\pi ft)$

The voltage across C, $V_C$, = $\frac{I_p}{2\pi fC} \sin(2\pi ft - 90°)$

If these voltages are all plotted on the same time scale, one obtains a set of sin waves such as that shown in Figure 38. The total voltage will be the sum of the three sine waves.

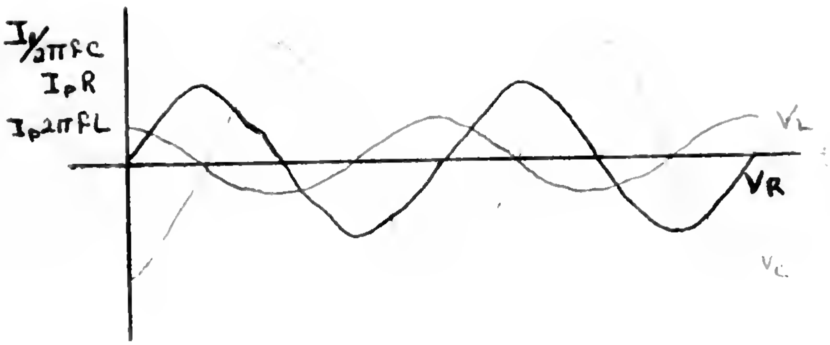
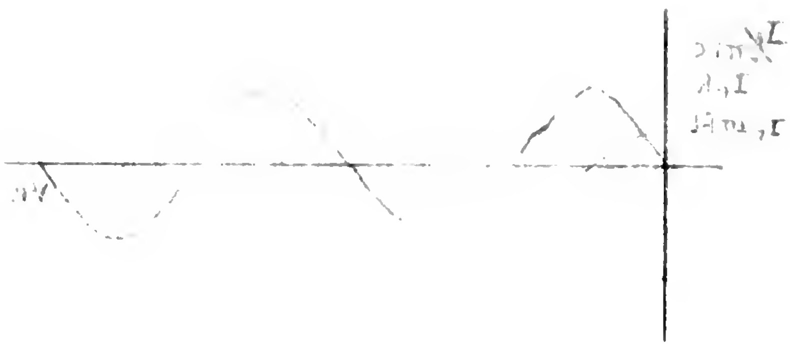



Figure 38

It is apparent that $V_C$ and $V_L$ are 180° out of phase. The maximum or peak voltage of $V_C$ is $\frac{1}{2\pi fC}I_p$ and the maximum voltage of $V_L$ is $2\pi fLI_p$. If these were equal, the two voltages would exactly cancel one another and the total voltage of the circuit would equal the voltage across R. This is illustrated in Figure 39. The greatest voltage that can appear across R is $V_S$, the voltage of the ac source. The greatest current



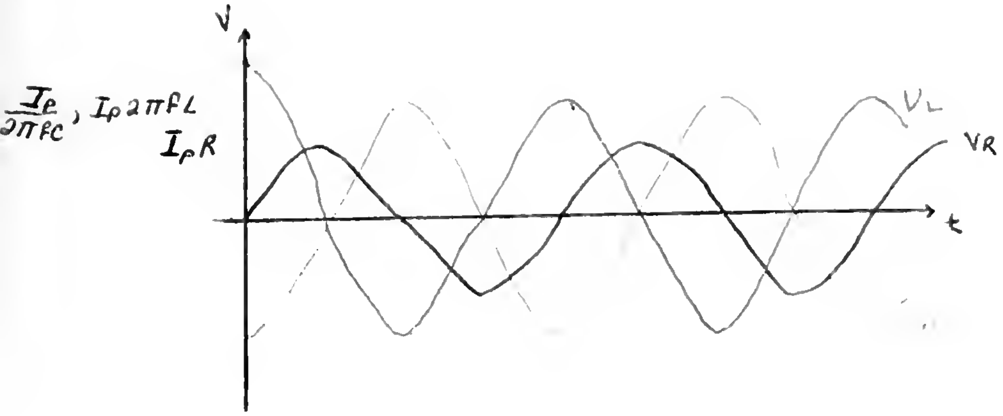



Figure 39

possible is therefore $\frac{V_S}{R}$. If $2\pi fL = 1/2\pi fC$, then the current in the circuit will be a maximum. Also note that the voltage across the capacitor and the inductor may be larger or smaller than $V_S$, but as long as $X_L = X_C$, they will cancel one another and $V_R$ will equal $V_S$.

If the same components are connected in parallel, the voltage across each will be the same, but the currents will be out of phase.

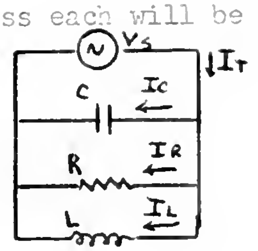



Figure 40

$$V_S = V_p \sin 2\pi ft$$

$$I_R = \frac{V_p}{R} \sin 2\pi ft$$

$$I_C = V_p 2\pi fC \sin(90° - 2\pi ft)$$

$$I_L = \frac{V_p}{2\pi fL} \sin(2\pi ft - 90°)$$

This time, if the currents are plotted on the same time scale, one obtains a set of sine waves such as that shown in Figure 41. The total current will be the sum of the three sine waves.

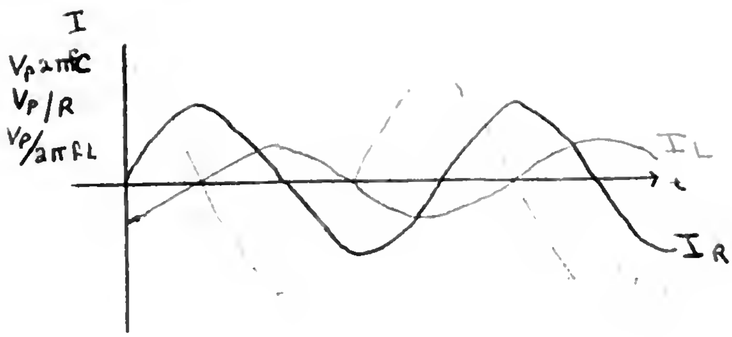



Figure 41

In this case, $I_C$ and $I_L$ are 180° out of phase. Now if $\frac{1}{2\pi fC} = 2\pi fL$, the current in C would be equal in magnitude and opposite in direction to the current in L. The total current would then be the same as the current through R. Here the current would be a minimum. Note, however, that the currents in C and L may be quite large compared to the current in R, but as long as $X_C = X_L$, these two will cancel each other and not effect the total amount of current drawn.

For a series circuit then, when $X_C = X_L$, the current is at a maximum and voltages much higher than $V_s$ may appear across C and L. For a parallel circuit, when $X_C = X_L$, the current drawn is a minimum but currents much higher than the total current drawn may flow through C and L. When $X_C = X_L$, the circuit is said to be in resonance.

Procedure.

The circuit illustrated in Figure 42 is used to show the process of charging a capacitor.

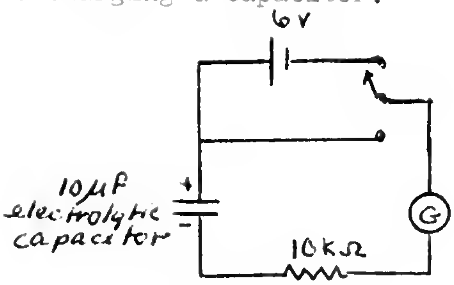



Figure 42

In using an electrolytic capacitor always be sure the positive potential is connected to the positive side of the capacitor. Construct this circuit. Close the switch. Observe the current flow, direction and range, as indicated by the galvanometer. When the current ceases to flow, measure the voltage across the capacitor with the switch still closed. Then open the switch and measure the voltage across the capacitor again. Close the switch so that the circuit is short-circuited. Again observe the magnitude and direction of the current. When the current ceases to flow, measure the voltage across the capacitor.

Using the step-down transformer as the ac voltage source (5v ac), construct the circuit shown in Figure 43. (For an explanation of transformers, see any of the references listed on page [illegible].) Do not use the electrolytic capacitor in an ac circuit.

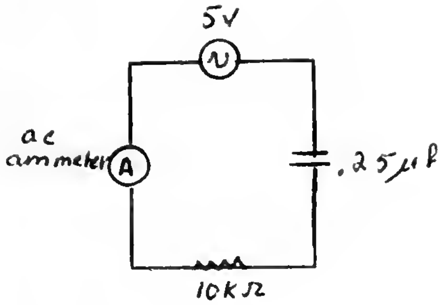



Figure 43

Use the vacuum tube voltmeter to measure the voltage across the capacitor, the resistor, and the whole circuit. Measure the current with the ac ammeter.

Now connect the capacitor and resistor in parallel as shown in Figure 44. Measure the current through each component, the total current, and the total voltage. From the voltage drop across the capacitor in each case and the current through it, calculate the reactance of the capacitor.

Connect two .25-μf capacitors in parallel with one another and put them in series with the ten kΩ resistor, as shown in Figure 45.

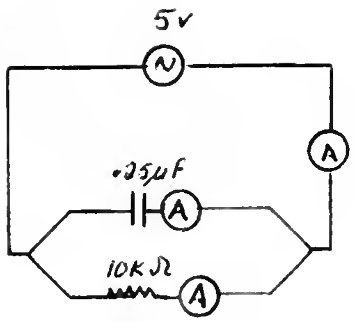



Figure 44

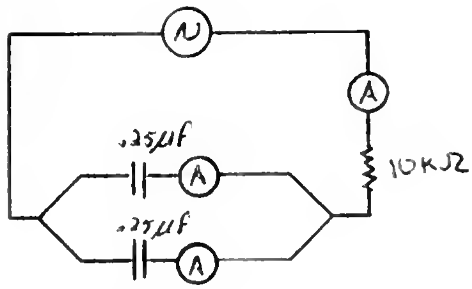
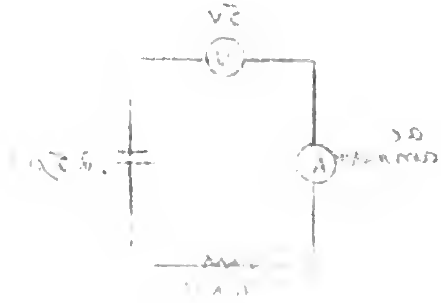


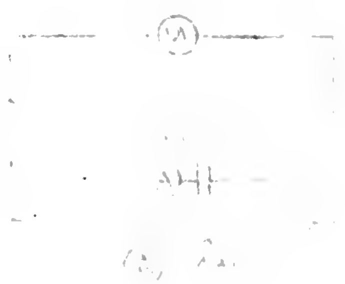

Figure 45

Treating this parallel arrangement of capacitors as a whole unit, calculate the reactance of the unit. Since $\frac{1}{2\pi fC} = X_C$, what may be said about the total capacitance of two capacitors connected in parallel?

The inductor used has an unknown inductance. Before beginning, measure the resistance of the inductor either with the Wheatstone bridge or with the ohmmeter setting of the V.T.M. Should this resistance be considered to be in series or in parallel with the inductance?

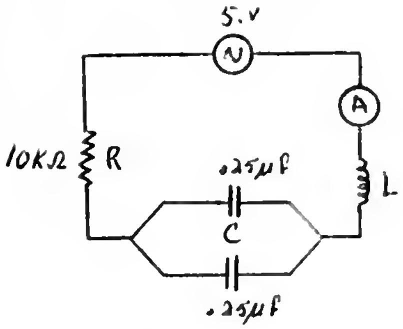
Connect the ten kΩ resistor and the inductor in series and in parallel with one another, and repeat the kinds of measurements made





for the capacitor. Calculate the reactance of the inductor in each case. From $X_L = 2\pi fL$ and f=60cps, calculate the inductance of the coil.

Construct the circuits shown in Figures 46-49, and measure the voltage across each component and the current through each. Explain your results on the basis of resonance considerations.




Note: The parallel arrangement of capacitors should be treated as one capacitor. (What is its equivalent capacitance?)

Figure 46

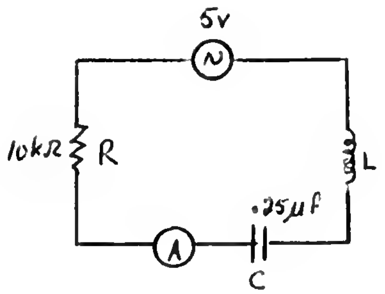



Figure 47

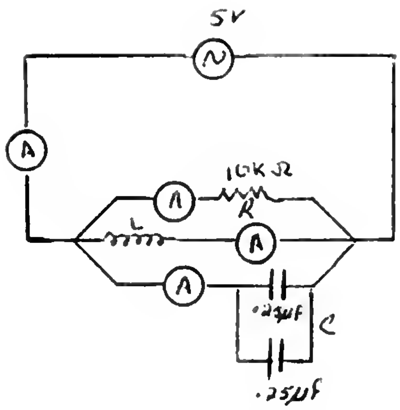
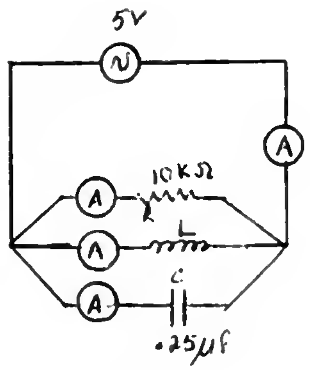
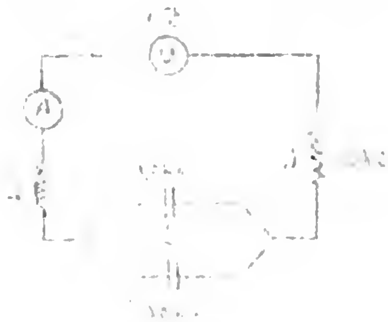


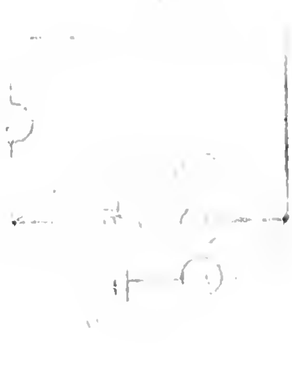

Figure 48




What is a possible reason for any discrepancies that appear between the current in the resistor and the voltage across it? ($V_{rms} = I_{rms}R$.)

Figure 49





The oscilloscope may be used to determine phase angles between voltages across different components in an ac circuit. This may be done in one of two ways. The signal from each component may be put on the vertical input, the horizontal sweep adjusted so that a stationary wave is obtained, and the relative positions of the maxima and minima observed. The other method is to put the signal from one component on the vertical plate and the signal from another component on the horizontal plate and to observe the shapes of the Lissajous figures thus obtained.

Try each of these methods using the series circuit which was most nearly in resonance. Why wouldn't this method work in observing phase angles in a parallel arrangement of components?

Calculations, data and conclusions

When a dc voltage was applied across the capacitor, current was observed to reach a maximum when the circuit was closed and decrease slowly to zero. When the current was zero, the voltage across the capacitor was equal to the applied voltage and it remained at that potential when the switch was opened. When the circuit was shorted, current reached a maximum again and decreased slowly to zero, but this time the needle of the galvanometer was deflected in the opposite direction. When the current had ceased to flow, the voltage across the capacitor was zero.

Data and calculations for the circuit shown in Figure 43:

Total voltage..... 6.2v
Voltage across C...4.2v
Voltage across R...4.2v
Current............0.4ma

$$X_C = \frac{V_C}{I_C} = \frac{4.2}{4\text{x}10^{-4}} = 10.5\text{k}\Omega.$$

Data and calculations for circuit shown in Figure 44:

Total voltage......5.7v
Total current......0.[illegible]ma
Current in R.......0.56ma
Current in C.......0.53ma

$$X_C = \frac{5.7}{5.[illegible]\text{x}10^{-4}} = 9.9\text{k}\,\Omega.$$

Data and calculations for circuit shown in Figure 45:

Total voltage............5.7v
Voltage across capacitors..2.5v
Voltage across R...........5.0v
Current....................0.45ma

$$X_{\text{both capacitors}} = \frac{2.5}{4.5\text{x}10^{-4}} = 5.6\text{k}\,\Omega$$

Since $X_C = \frac{1}{2\pi fC}$, $C = \frac{1}{2\pi fX_C}$. Since $X_C$ is approximately one half as great for two .25-$\mu$f capacitors in parallel as for one .25-$\mu$f capacitor, the capacitance of the two together must be twice as great as for the single capacitor. The total capacitance of two capacitors in parallel is the sum of the individual capacitances, in this case, .5$\mu$f.

The resistance of L was found to be 500$\Omega$. The resistance of L is in parallel with the inductance since the same voltage must always appear across each.

Data and calculations for the inductor and resistor in series:

Total Voltage.......5.2v

Voltage across R....4.2v

Voltage across L....1.[illegible]v

Current.............0.45ma

$$X_L = \frac{V_L}{I_L} = \frac{1.[illegible]}{4.5\times10^{-4}} = 3.[illegible]k\Omega.$$

Data and calculations for the inductor and resistor in parallel:

Total voltage.......5.2v

Current in R........0.[illegible]ma

Current in L........1.3ma

Total current .......1.5ma

$$X_L = \frac{5.2}{1.3\times10^{-3}} = [illegible]\Omega.$$

Data for circuit of Figure 4[illegible]:

(C = .5$\mu$f)

Total voltage......5.2v

Voltage across R....4.[illegible]v

Voltage across C...[illegible].2[illegible]

Voltage across L...1.[illegible]v

Current............0.53ma

Data for circuit of Figure 47:

(C= .25$\mu$f)

Total voltage......[illegible].1v

Voltage across R...[illegible].9v

Voltage across C...[illegible].0v

Voltage across L...1.[illegible]v

Current............0.[illegible]6ma

Data for circuit of Figure 4[illegible]:

(C = .5$\mu$f)

Total voltage......4.[illegible]v

Current in R.......0.[illegible]ma

Current in C.......1.15ma

Current in L.......1.3ma

Total current......0.74ma

Data for circuit of Figure 49:

(C = .25$\mu$f)

Total voltage......5.2v

Current in R.......0.55ma

Current in C.......0.55ma

Current on L.......1.3ma

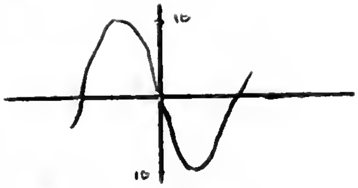
Total current......1.[illegible]ma

Because the reactances of the coil and the parallel arrangement of the two capacitors are more nearly equal, the combination of these gives rise to circuits which are more nearly in resonance than the circuits using only one .25$\mu$f capacitor. This is substantiated by the greater total current for the series circuit using the two capacitors, and by the smaller total current in the parallel circuit using the two capacitors.

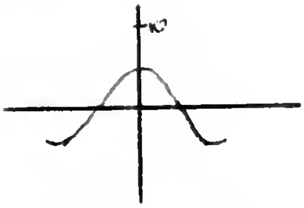
Oscilloscope patterns

The series circuit shown in Figure 45 was used in the work with the oscilloscope. Because the currents, not the voltages, are out of phase in a parallel circuit, and because the oscilloscope measures voltages, this method cannot be used in parallel arrangements.

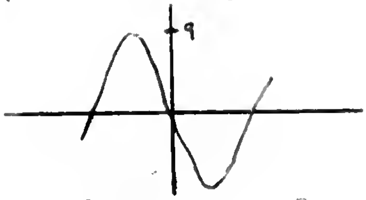
The pattern was a sine wave. The multiplier was set to x100 and the amplitude of the total voltage was then 20 divisions peak-peak. The pattern was centered as shown at left, after which the only changes made were in the components across which the input was taken; no changes were made in the adjustment of the scope.



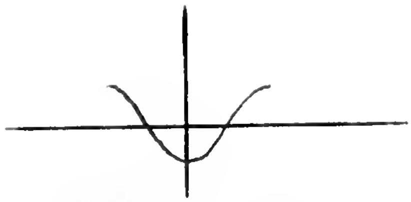

Total voltage




Voltage across C
(10 divisions peak-peak)



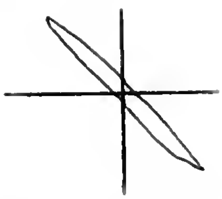

Voltage across R
(18 divisions peak-peak)



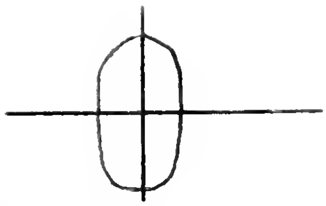
Voltage across L
(10 divisions peak-peak)

Lissajous patterns

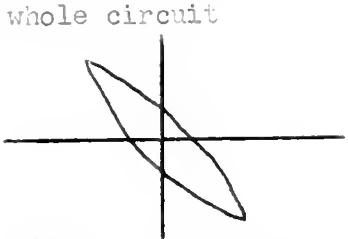
The voltage across the whole circuit was put on the vertical input and the voltage on the horizontal input was varied:



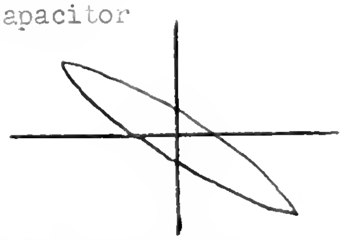
Horizontal across whole circuit



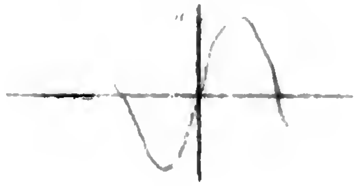
Horizontal across capacitor

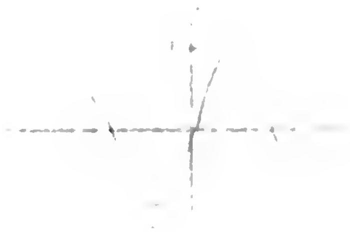


Horizontal across resistor



Horizontal across inductor





The resistor used probably has an inductance associated with it. This is demonstrated by the Lissajous patterns since the resistor versus the total voltage resembled the inductor versus the total voltage, and L is known to have a resistance associated with it.

## CONDUCTIVITY MEASUREMENTS

To measure the conductivity of a solution, it is only necessary to measure the resistance of a certain volume of the solution. The cell usually used for this consists of two parallel platinum electrodes, coated with platinum black, of some specific area and separated by some particular distance. This cell is placed in the solution and the resistance measured. A Wheatstone Bridge is usually used for this resistance measurement wiht an ac source and some suitable ac detector. However, the cell also acts as a capacitance since it is, after all, two parallel plates separated by an electrolyte. For this reason, it is impossible to balance the bridge exactly just by varying the resistance. The cell may be represented as a parallel arrangement of a resistor and a capacitor since the same potential is always across each. The effect of a capacitor in such a circuit is to put the voltage and current out of phase with one another. The bridge circuit, ignoring temporarily the detector, is the one shown in Figure 50.

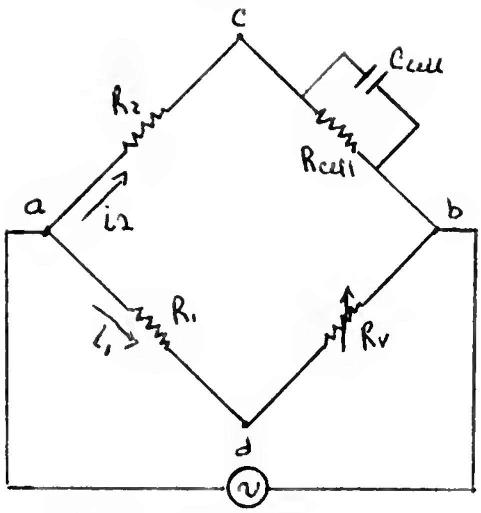



Figure 50

It should be recalldd that in a parallel circuit containing a capacitor and a resistor, the voltages are in phase in each component but the currents are out of phase. Therefore, $i_1$ will be out of phase with $i_2$, and although the total voltage drops will be in phase, the voltages across $R_1$ and $R_2$ will be out of phase with each other and the voltages across the cell and $R_v$ will be out of phase. Therefore, it will be impossible to balance the bridge unless the currents are first brought into phase with one another. It is possible to adjust $R_v$ until $i_{cd}$ is a minimum, but not so that $i_{cd}$ is zero. The value of $R_v$ which gives this minimum (assuming $R_1 = R_2$ for convenience) will represent the impedance of the cell, not the pure resistance.

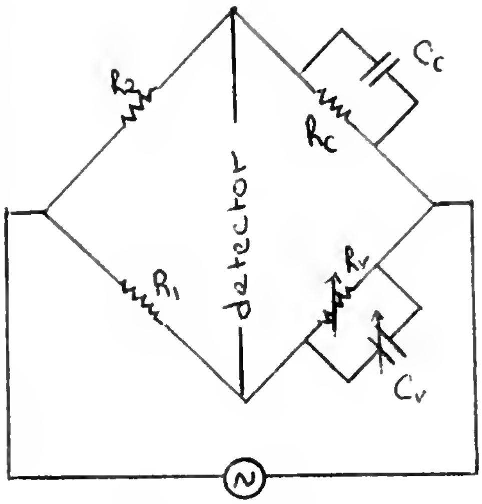



Figure 51

If appropriate variable capacitors are available, this may be compensated for by the circuit of Figure 51. $C_c$ and $R_c$ are the capacitance and resistance of the cell respectively; $R_v$ is a decade box and $C_v$ is a variable capacitor. The capacitor is varied until the voltage reaches a minimum (the currents are in phase), and then $R_v$ is varied until there is no potential difference across the detector. Because the conductivity and hence resistance of the cell is all that we are interested in, it is not necessary to determine the absolute value of the capacitance.

Procedure

The same Wheatstone bridge that was used previously may be used in this experiment. A 1000cps signal generator is used as the voltage source and either headphones (1000cps is an audible signal) or an oscilloscope may serve as the detector.

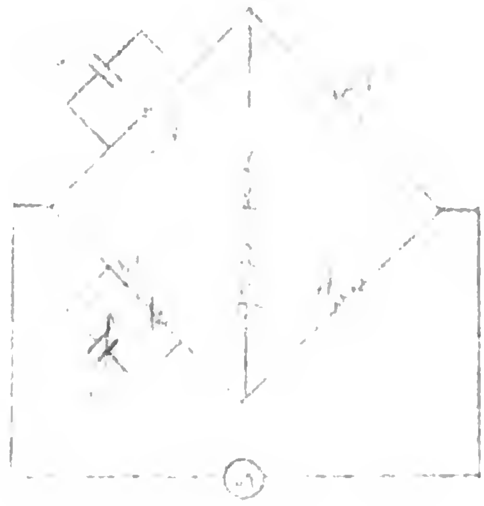
The conductance of the following solutions should be measured:

0.1 N KCl (in order to calculate the cell constant and show concentration effect)
0.01 N KCl
0.001 N KCl

First use the bridge without the variable capacitor, using both headphones and the oscilloscope as the detector. Which detector gives the smallest range in the readings?

Using the oscilloscope as the detector, repeat the measurements for the 0.001 N KCl using the variable capacitor.

Decide which circuit gives the most meaningful and easy to take readings, and use it to titrate 0.02 N HCl with 0.0200 N NaOH conductometrically.



Calculations, data and conclusions

The following resistance values were determined for the cell immersed in each solution:

| Solution | Resistance (Ω) oscilloscope | Resistance (Ω) head phones |
|---|---|---|
| 0.1 F KCl | 7.3 ± .1 | 7.0 ± .5 |
| 0.01 F KCl | [illegible]5.2 ± .1 | - |
| 0.001 F KCl | 639 ± 3 | - |

A better minimum could be determined using the oscilloscope as the detector.

Resistance of cell in 0.001 F KCl:

| Trial | Using $C_v$ | Not using $C_v$ |
|---|---|---|
| I | 613.5 ± .2 Ω | 610 ± 1 Ω |
| II | 613.1 ± .3 Ω | 617 ± 1 Ω |
| III | 61[illegible] ± .4 Ω | 613 ± 1 Ω |

A minimum was more easily observed when the capacitor was used. However, the decade box is not really accurate to more than about 2Ω, and it was very difficult to observe a minimum when varying the capacitance. Also, the bridge still could not be balanced completely. Therefore, the measurements even when using $C_v$ are probably only significant to three places, and the only advantage in using $C_v$ is that the minimum is easier to observe.

Variations in the above readings might have been caused by changes in solution temperature since the cell was not kept in a constant temperature bath.

A more elaborate bridge would be necessary for precise, absolute conductivity measurements. Such a bridge would have to eliminate the "noise" of the present apparatus, and would require a precision (and expensive) decade box, a variable resistor with a larger range, etc. However, this bridge is quite adequate for conductometric titrations where relative, not absolute, conductivity values are required.

Data - Titration of 0.02 M HCl with 0.0200 M NaOH

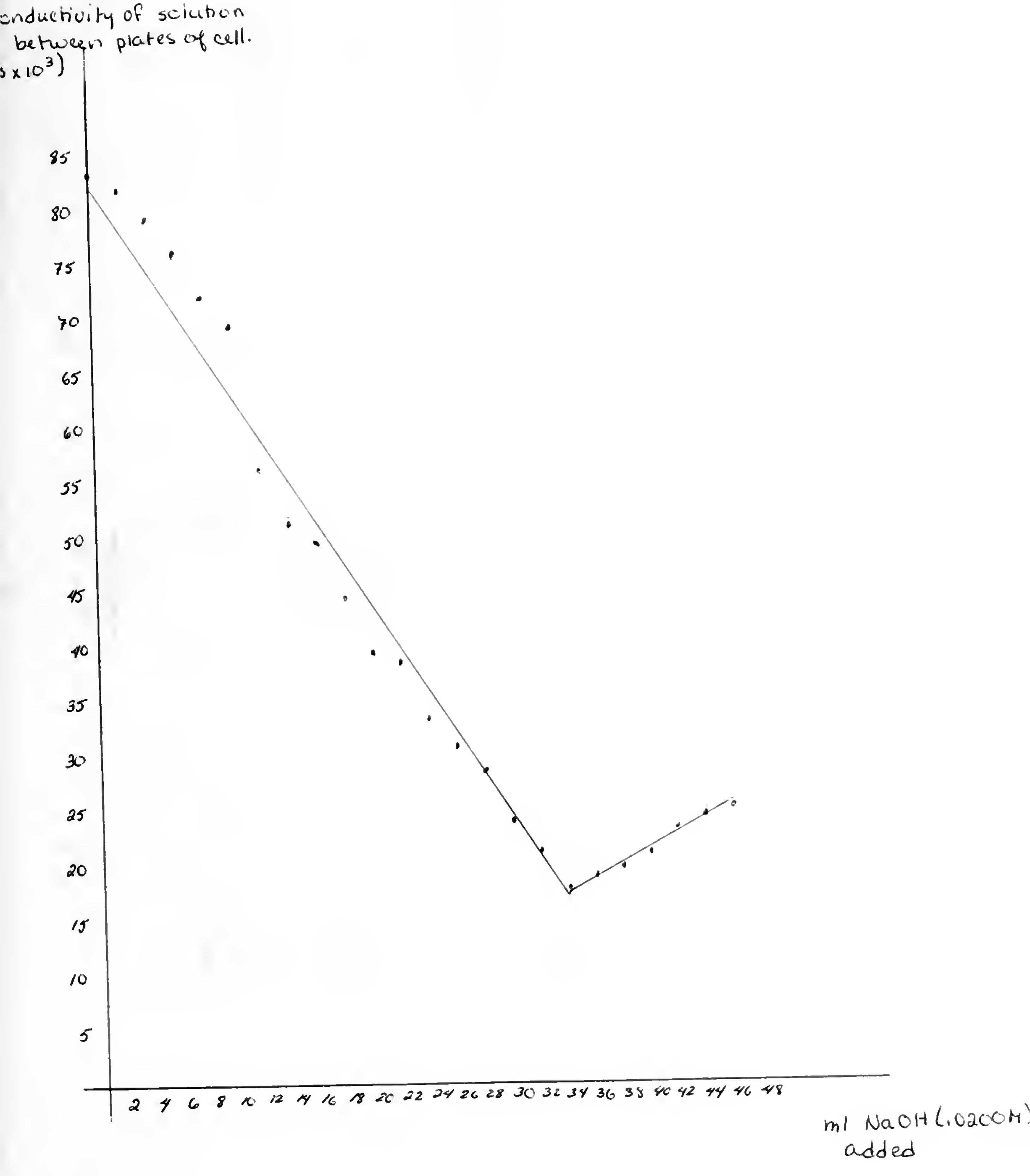
25.00 ml of HCl were used

| Ml NaOH | Resistance ohms | Conductivity (1/R) mhos |
|---|---|---|
| 0.00 | 12.0 | .083 |
| 2.00 | 12.2 | .082 |
| 4.00 | 12.6 | .079 |
| 6.00 | 13.1 | .076 |
| 8.00 | 13.9 | .072 |
| 10.00 | 14.6 | .069 |
| 12.00 | 18.0 | .056 |
| 14.00 | 19.1 | .052 |
| 16.00 | 20.5 | .049 |
| 18.00 | 23.0 | .044 |
| 20.14 | 25.7 | .039 |
| 22.00 | 27.2 | .038 |
| 24.00 | 30.3 | .033 |
| 26.00 | 31.9 | .031 |
| 28.00 | 36.8 | .028 |
| 30.00 | 42.5 | .024 |
| 32.00 | 48.5 | .021 |
| 34.00 | 56.6 | .0176 |
| 36.00 | 54.8 | .0183 |
| 38.00 | 51.3 | .0195 |
| 40.00 | 46.9 | .021 |
| 42.00 | 43.0 | .023 |
| 44.00 | 41.6 | .024 |
| 46.00 | 39.4 | .025 |

Because of experimental difficulties, the solution was probably not always stirred completely enough after each additon of NaOH.

Calculations:

$$N_{HCl} = \frac{34}{25}(.02) = 0.0272.$$




CONDUCTOMETRIC TITRATION

DIODES, RECTIFIERS, AND A DC POWER SUPPLY

Because most chemical instruments require the use of direct currents, it is often necessary to convert the readily available ac current to dc current.

This may be done by using diodes, devices which conduct current in one direction only. Explanations of vacuum tube diodes may be found in Malmstadt and Enke's Electronics for Scientists or in Strobel's Chemical Instrumentation. An excellent discussion of semiconductors and junction diodes appears in "Journal of Chemical Education", 46, 10 (1969).

If a diode is inserted into an ac circuit, current will flow in the circuit for half of the cycle, and no current will flow during the other half cycle. During the half of the cycle that point a of Figure 52 is positive with respect to point b, current will flow in the circuit and there will be a voltage drop across R. When a is negative with respect to b, no current flows and the voltage drop across R is zero. The net result is that the current in the circuit flows in only one direction, but it is not constant. Instead, it appears in pulses and is known as a pulsating dc current. Since the voltage drop across R is dependent on the current, this voltage is also pulsating. (See Figure 53)

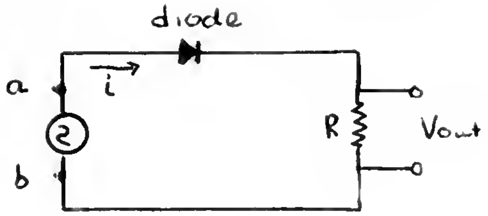



Figure 52

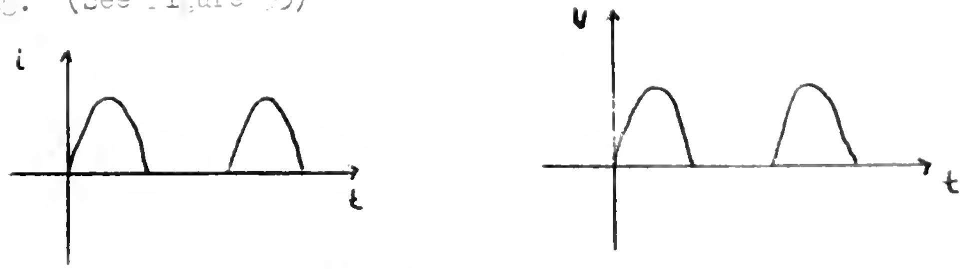
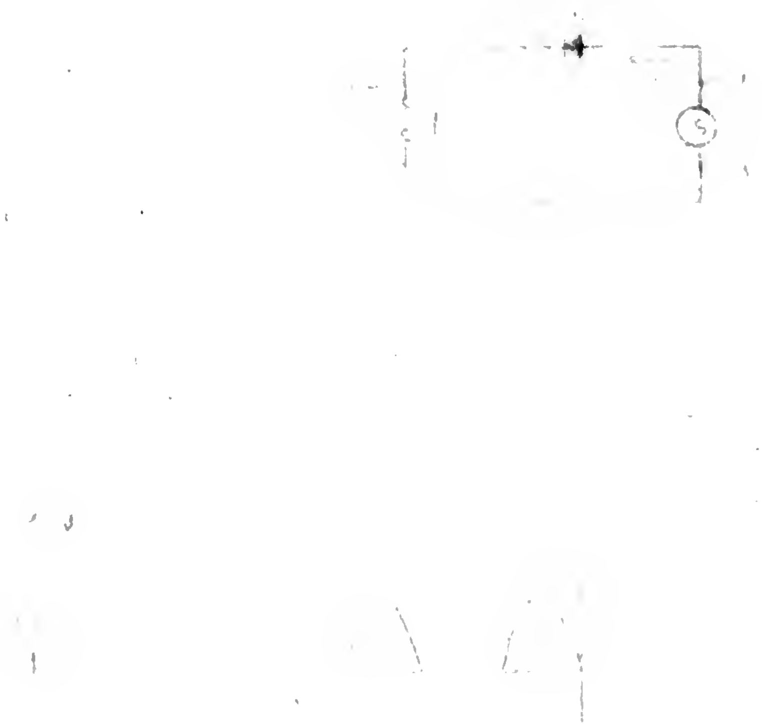



Figure 53

Two diodes may be connected in such a way as to give full-wave rectification. This is illustrated in Figure 54.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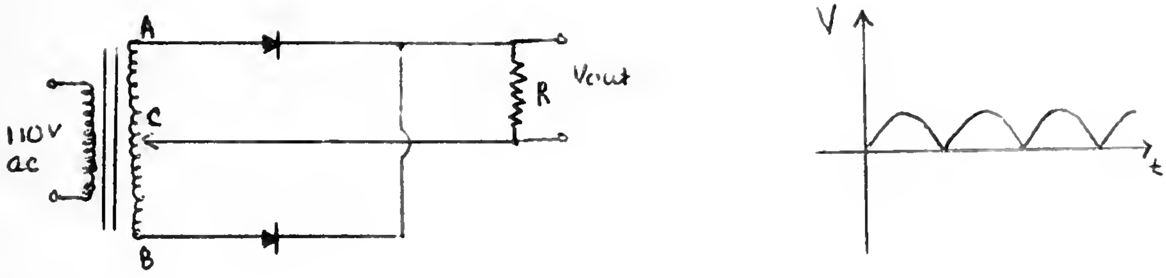



Figure 54

Here C is connected to the transformer so that $V_{AC} = V_{BC} = \frac{1}{2} V_{AB}$. When A is positive with respect to B, it is positive with respect to C, and current flows from A to C through R. During the other half of the cycle, B is positive with respect to C and current flows through R from B to C. The current through R is in the same direction each time. It should be noted that becarse $V_{AC}$ is only $1/2(V_{AB})$, the voltage across R is one half as great as in the half-wave rectifier of Figure 52, but in this case, both half cycles give rise to out put voltage.

Another type of full-wave rectifier is the bridge rectifier shown in Figure 55.

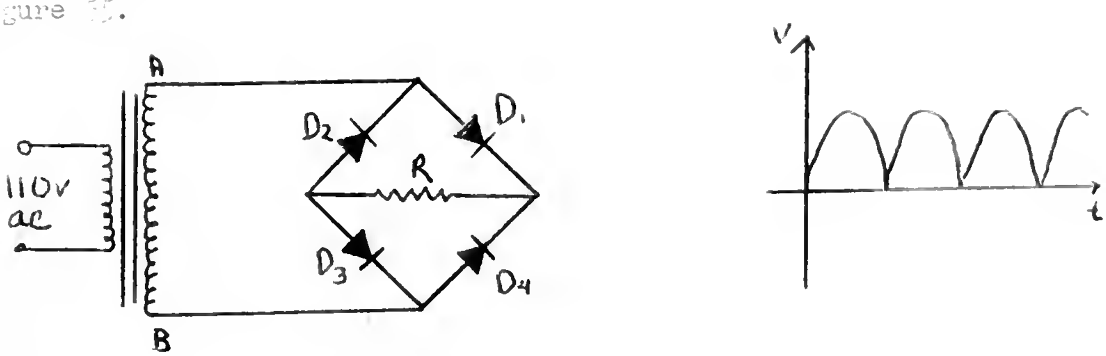
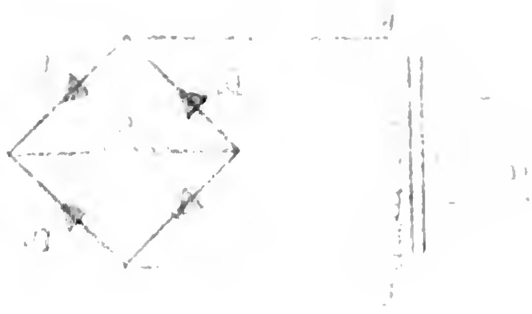



Figure 55

When A is positive with respect to B, current flows through $D_1$, R, and $D_3$ to B. When B is positive with respect to A, current flows from B through $D_4$, R, and $D_2$ to A. In each half cycle it flows through R in the same direction, and this gives a full-wave rectifier which allows one to use the entire voltage drop from A to B.



The rectified currents are indeed in one direction, but they vary in intensity. For most work, this pulsating dc is not adequate, so various filters are used to give a more even voltage supply.

One such filter is the capacitor filter. If a capacitor is connected in parallel with the load resistor, it charges as the current in the circuit increases, and then begins to discharge through $R_L$ when the current (and therefore the voltage) decreases. This filter is especially effective where $R_L$ is large and the amount of current flowing through it is small; since if only small currents are drawn from the capacitor, the voltage across it will stay relatively constant.

An inductance filter uses an inductor in series with $R_L$. This opposes changes in the current through $R_L$ and is therefore most effective when $R_L$ is small and the changes in current are therefore relatively large.

A $\pi$ filter, shown in Figure 5c, is a combination of the L and C filters which keeps the "ripple" voltage relatively low regardless of the load resistance.

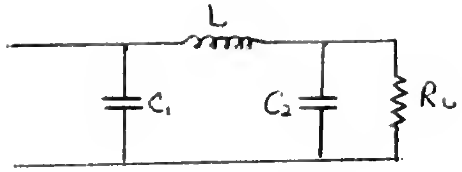



Figure 5c

Procedure

Using the breadboard circuit, construct half-wave, full-wave, and bridge full-wave rectifiers, observing the output voltage with the oscilloscope (let $R_L$ = 100$\Omega$). If the patterns appear upside down on the oscilloscope, replug the transformer so that they are rightside up. (Why does this correct it?)

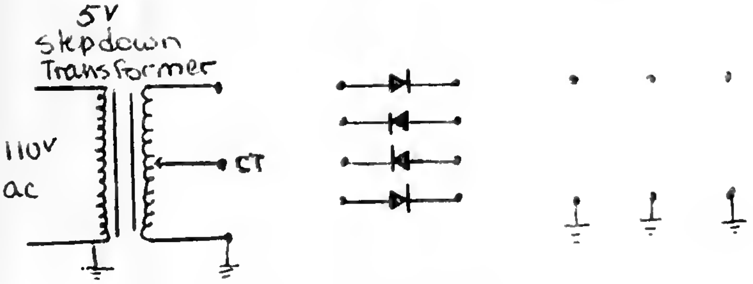
Leave the bridge rectifier set up and insert a capacitor filter using a 200 $\mu$F electrolytic capacitor, being sure to put it in correctly. Observe any defferences when $R_L$ is changed from 100$\Omega$ to 1000$\Omega$. Also measure the input and output voltages.

Put an L filter in the same rectifier. Again change the siae of $R_L$ from 100 Ω to 1000 Ω, and note any difference in the ripple voltage. Measure the input and output voltages.

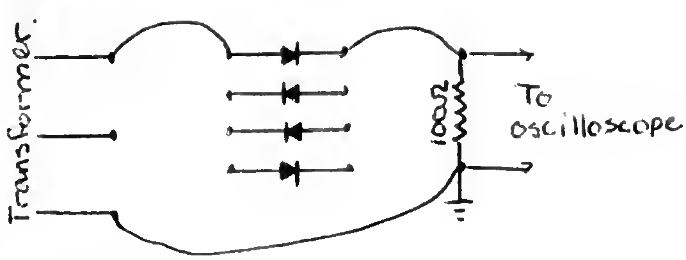
Next connect the π filter. Again vary $R_L$ and measure the input and output voltages.

Data and conclusions

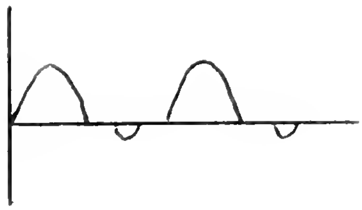
The breadboard circuit used was adapted from the Heath EUW-15 Universal Power Supply.[6]




Breadboard Circuit

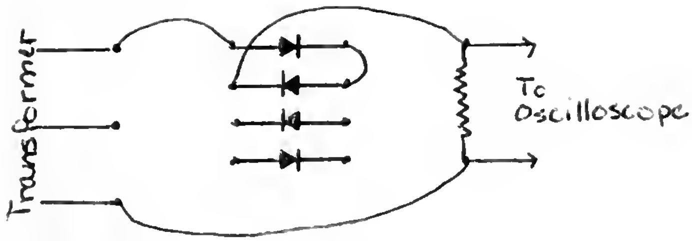



Breadboard circuit connected as half-wave rectifier

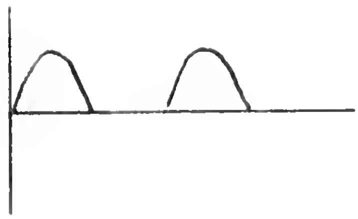


Oscilloscope pattern

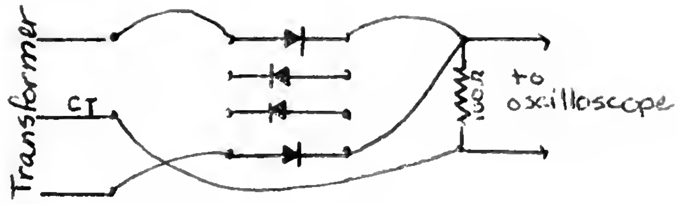
The oscilloscope pattern indicated that the diode was not strong enough at that potential to stop all the reverse current, so two diodes were used in series:



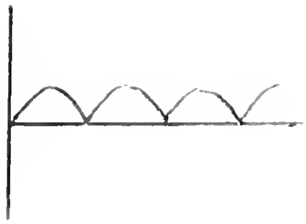

Breadboard circuit for half-wave rectifier using two diodes in series



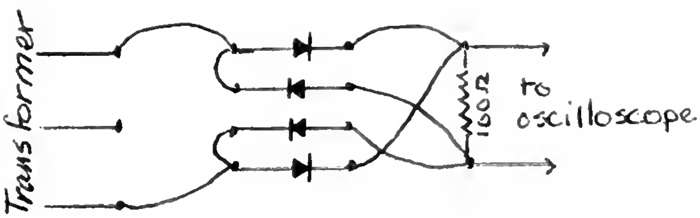
Oscilloscope pattern



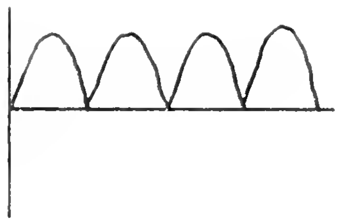

Breadboard circuit for full-wave rectifier



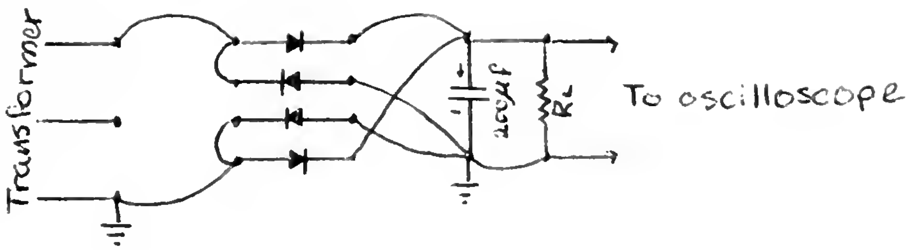
Oscilloscope pattern

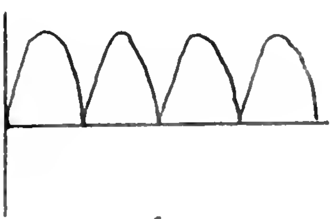



Breadboard circuit for bridge full-wave rectifier

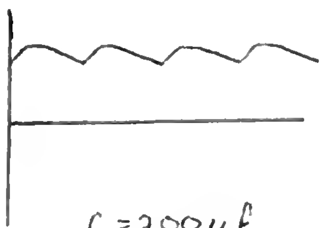


Oscilloscope pattern

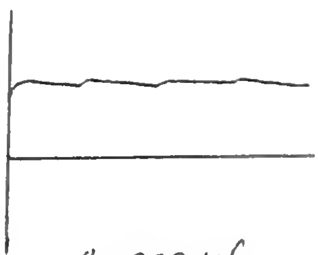


no C
R = 100Ω

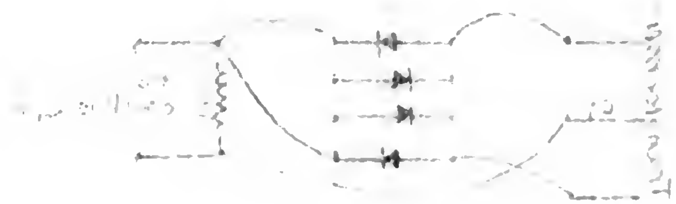


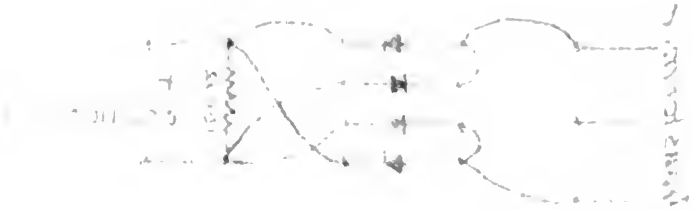
C = 200μf
R = 100Ω

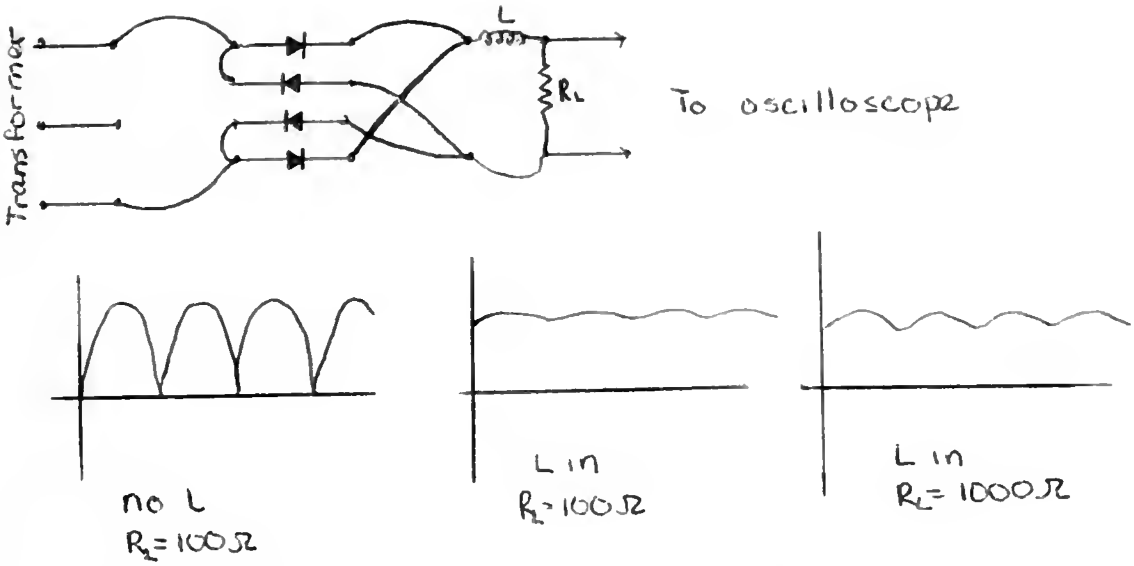


C = 200μf
R = 1000Ω

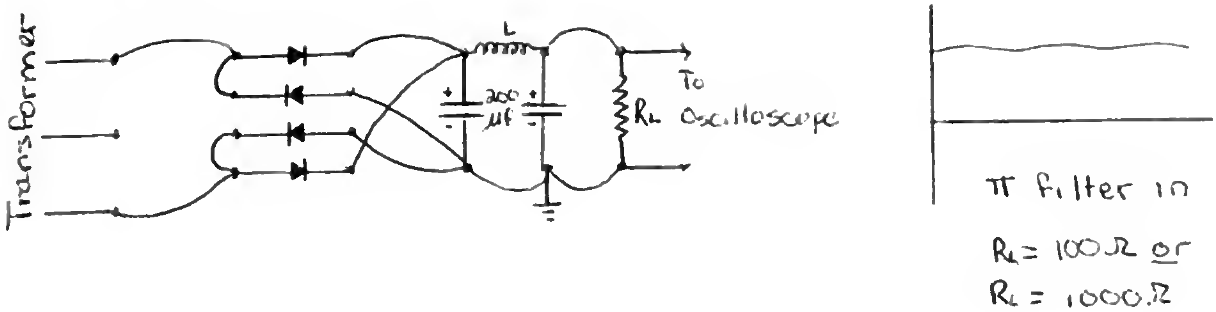
Breadboard circuit and oscilloscope patterns for bridge full-wave rectifier with C filter



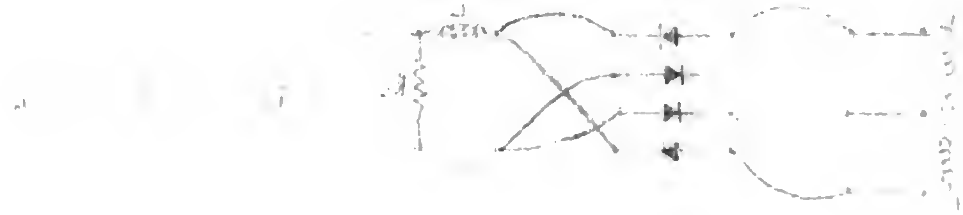


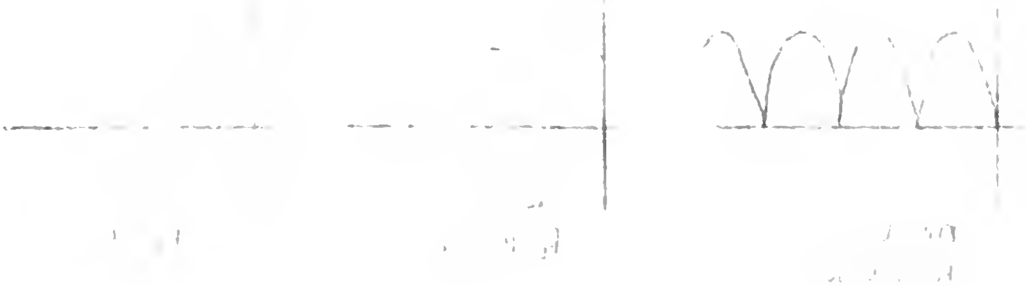



Breadboard circuit and oscilloscope patterns for bridge full-wave rectified with L filter




Breadboard circuit and oscilloscope pattern for bridge full-wave rectifier with π filter





## CONCLUSION

The experiments discussed in this paper have been presented in the order in which they should be done. A possible expansion of these experiments would be to determine the characteristics of a triode and to use this triode as a simple one-stage amplifier. After such an amplifier has been constructed, the student should be able to understand more complicated amplifiers, and the concepts of feedback and coupling could be introduced.

If the experiments are expanded to include such work, the student should have about two weeks available to devote to methods which are particularly interesting to him, investigating these methods in more detail. This might include the use of an operational amplifier in such diverse methods as constant current coulometry and differential thermal analysis, or studies with gas chromatography.

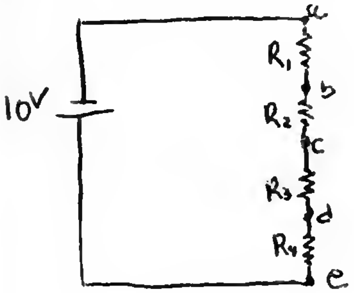
The attempt made in this work was to design a laboratory course which will provide the student with enough basic understanding of the principles on which instruments are based so that he may then work independently with new instruments or new applications of instruments.

## Solved Problems

Brophy, Basic Electronics For Scientists, p. 43.

1-9 Battery Voltage - 10 V

Output voltages: 1.0, 2.0, 5.0, 10.0 volts.




$V_{ad} = 5V$ if $V_{ab} + V_{cd} + V_{bc} = V_{de}$

or if, since $i$ is same in each resistor, $R_1 + R_2 + R_3 = R_4$

$$(R_1 + R_2 + R_3)\, i = i R_4 = 5V$$

If $V_{ab} = i R_1 = 1V$

and $V_{ac} = i(R_1 + R_2) = 2V$

then $R_1 = R_2$

$i(2R_1 + R_3) = 5$

$R_3 = 3R_1$

Choose resistors such that the ratio is

$R_1 : R_2 : R_3 : R_4 = 1:1:3:5$

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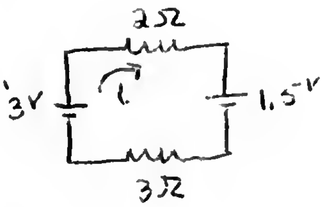
1-10.




$3V - 2i - 1.5V - 3i = 0$

$5i = 1.5$

$i = 0.3\ a$

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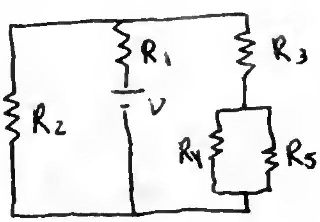
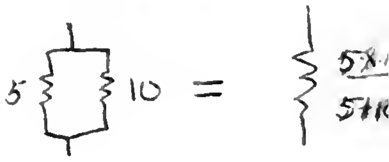
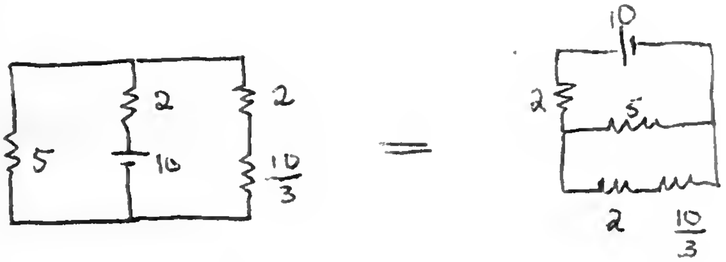
-14



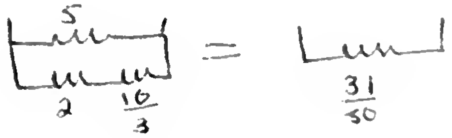

V = 10
$R_1 = 2$
$R_2 = 5$

$R_3 = 2$
$R_4 = 5$
$R_5 = 10$






$$\frac{\frac{16}{3}+5}{\frac{16}{3}(5)} = \frac{31}{80}$$




$$\frac{80}{31} + \frac{62}{31} = R_T = \frac{142}{31}$$

$$i = \frac{V}{R_T} = \frac{10}{\frac{142}{31}} = 2.18a$$

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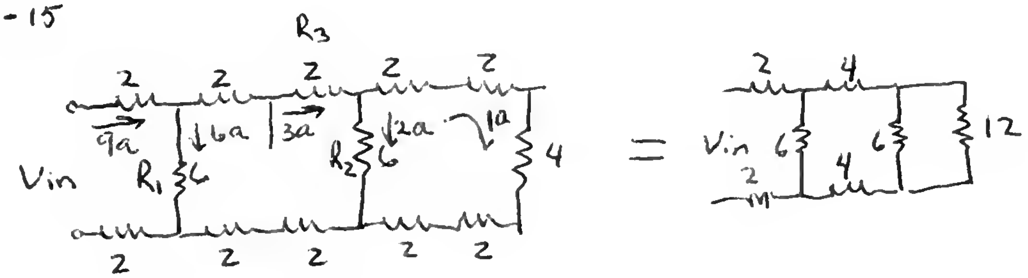
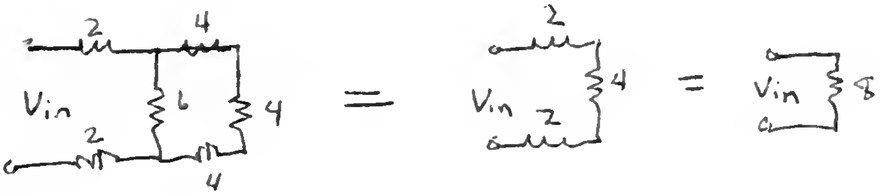
1-15




$$\frac{1}{R_{eq}} = \frac{12+6}{12 \times 6} = \frac{18}{72}$$

$$R_{eq} = 4$$




Total resistance = 8Ω

if one amp flows in 4Ω resistor, then 2amps flows in $R_2$ and 3amps must flow in $R_3$. ∴ 6 amps flow in $R_1$ and the total current is 9 amp.

$$V = 9 \times 8 = 72V$$

Malmstadt and Enke, Electronics for Scientists, p. 37

1-1. $R = 200\,\Omega$ $\quad I_{\frac{1}{2}\,scale} = \dfrac{50\times10^{-3}}{200} = 2.5\times10^{-4} = 250\,\mu a$

$V = 50\,mv$

$I_{full\,scale} = 500\,\mu a.$

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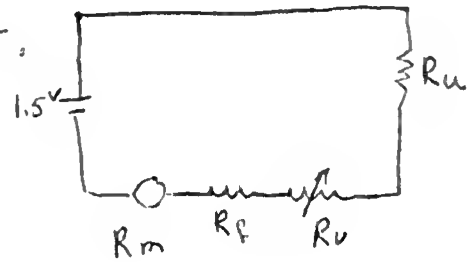
1-5.



meter 0 - 1 ma

$R_m = 100\,\Omega$

$R_f = 1000\,\Omega$

when $R_u = 0$, $R_v$ varied until $i = 1\,ma$

$R_m + R_f + R_v = \dfrac{1.5^v}{1\,ma}$

$100 + 1000 + R_v = 1500$

$R_v = 400$ $\quad$ For $\frac{1}{2}$ scale deflection at this voltage, $R_u = 1500$

if V decreases to 1.4V,

and $R_v$ adjusted so $i = 1\,ma$ when $R_u = 0$,

$R_m + R_f + R_v = \dfrac{1.4}{1} = 1400$

$R_v = 300\,\Omega$ $\quad$ For $\frac{1}{2}$ scale deflection at this voltage, $R_u = 1400$

# FOOTNOTES

[1]Malmstadt and Enke, *Electronics for Scientists*, pp. 4 and 5.

[2]*Ibid.*, pp. 5 and 474-47[illegible].

[3]Sears, *Electricity and Magnetism*, p.24[illegible].

[4]Reilley and Sawyer, *Experiments for Instrumental Methods*, p. 29[illegible].

[5]"Students' Potentiometer and Accessories," Catalog E-50 (1), Leeds and Northrup Company, 1945, p. 5

[6]Malmstadt and Enke, p. 502.

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2. Malmstadt, H. V., and Enke, C. G., Electronics for Scientists, W. A. Benjamin, Inc., New York, 1962.

3. Reilley, C. N. and Sawyer, D. T., Experiments for Instrumental Methods, McGraw-Hill Book Company, Inc., New York, 1961.

4. Sears, F.W., Electricity and Magnetism, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1946.

5. Meites, L. and Thomas, H.C., Advanced Analytical Chemistry, McGraw-Hill Book Company, Inc., New York, 1958.

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7. Gurnee, E.F., "Fundamental Principles of Semiconductors", Journal of Chemical Education, 46 (February, 1969), pp. 80-85.